“ESTIMATION OF TURBOMACHINERY FLOW LOSSES THROUGH CASCADE TESTING”

A lecture by

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for two day seminar on

Loss Mechanisms in Steam and Gas Turbines

held at
M.S.Ramaiah School of Advanced Studies

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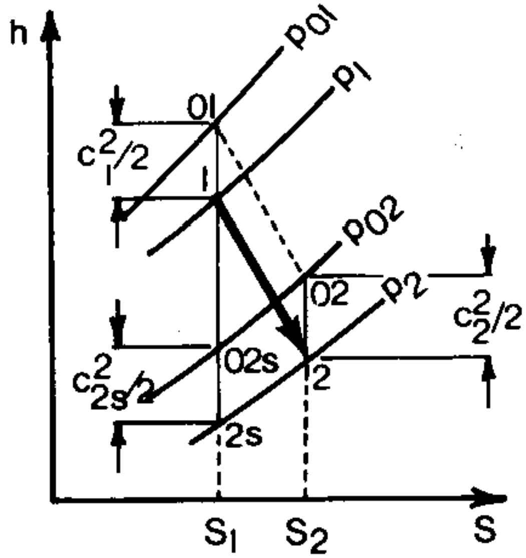
Types of losses in turbomachinery

Losses associated with boundary layers / viscous phenomena
- Friction, wakes, separation, secondary flows, mixing

Losses associated with compressibility effects
- Shock losses

Miscellaneous losses
- Tip clearance flows, disk-friction, partial admission, incidence

Representation of loss and efficiency



Turbine

Pressure loss coefficient

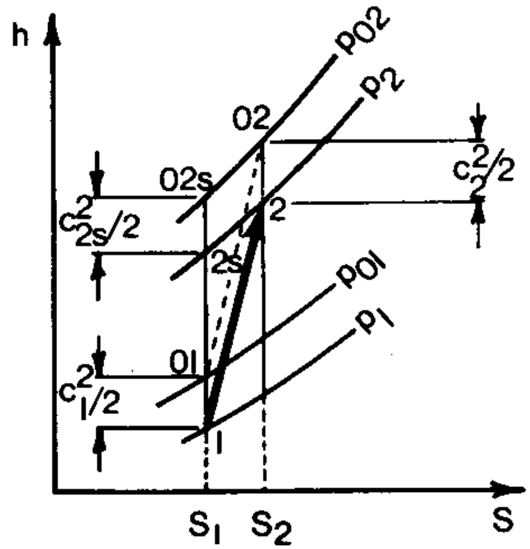
$\omega = (P_{01} - P_{02}) / (P_{02} - p_2)$

Energy loss coefficient

$\zeta = (h_2 - h_{2s}) / \frac{1}{2} C_2^2$

Efficiency

$\eta_t = (h_{01} - h_{02}) / (h_{01} - h_{02s})$



Compressor

Pressure loss coefficient

$\omega = (P_{01} - P_{02}) / (P_{01} - p_1)$

Energy loss coefficient

$\zeta = (h_2 - h_{2s}) / \frac{1}{2} C_1^2$

Efficiency

$\eta_c = (h_{02s} - h_{01}) / (h_{02} - h_{01})$

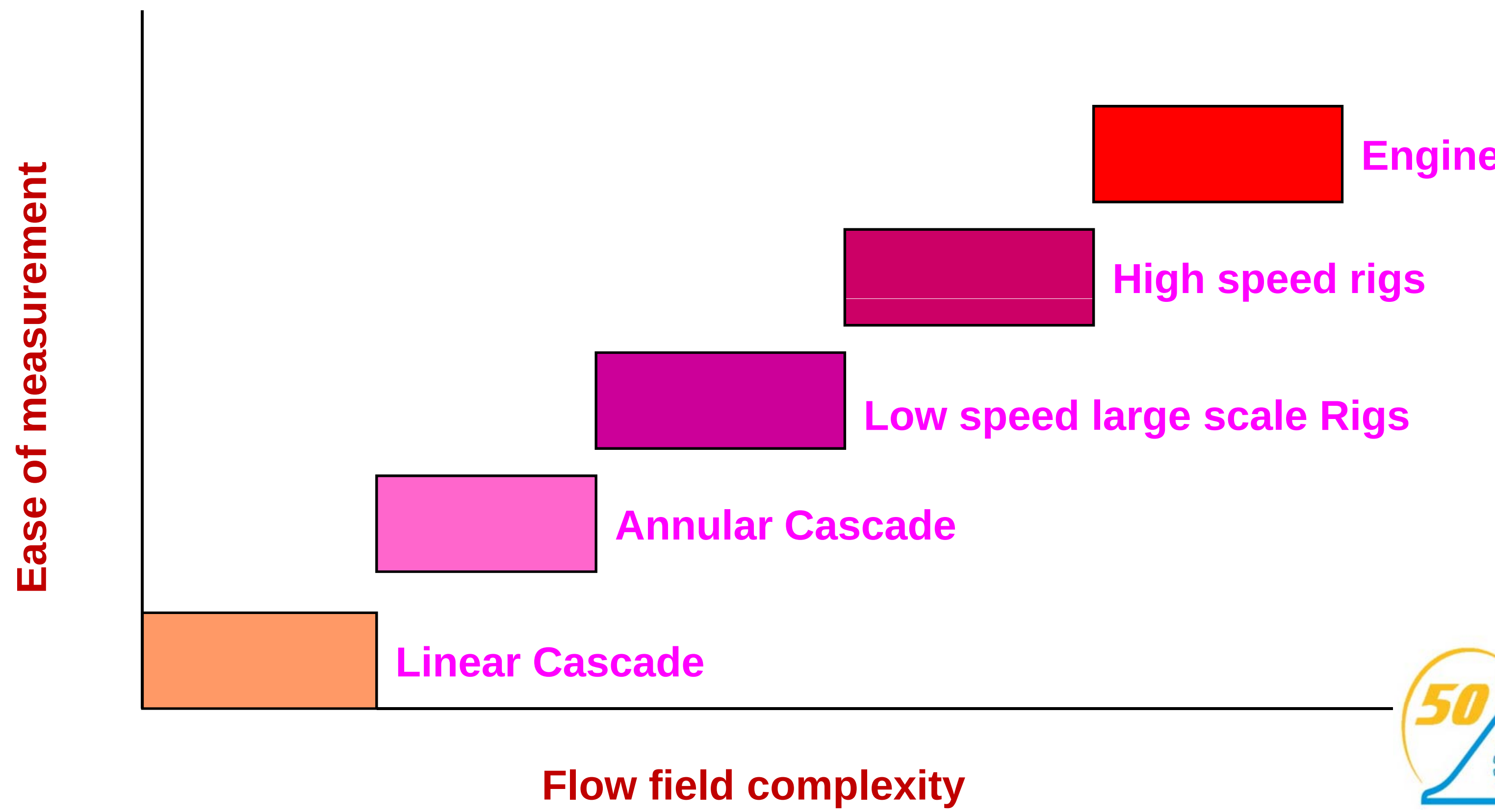
Stages of tests to understand turbo machinery flows

Linear Cascade
Quick and easy technique
excellent for parametric study
Simulation of 3D flow not possible

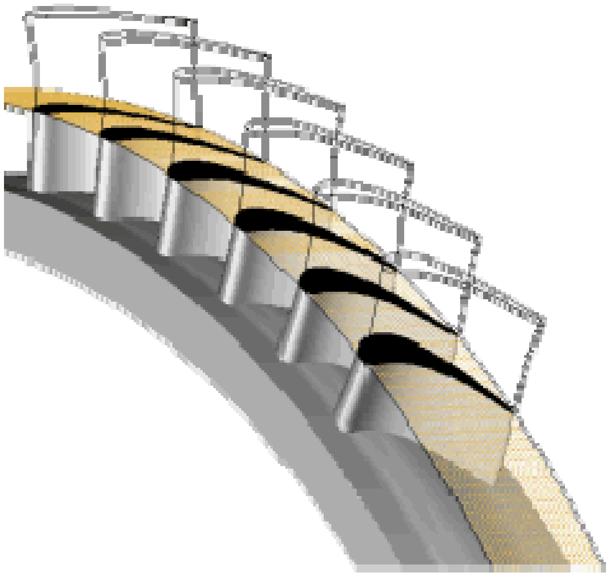
Annular cascade tunnel
A closer approximation to actual condition
Model design and experimentation complex
Does not include the rotation effect

Low speed large scale test rig
Closer to the engine condition
Enables detailed measurements
Simulates engine Reynolds number

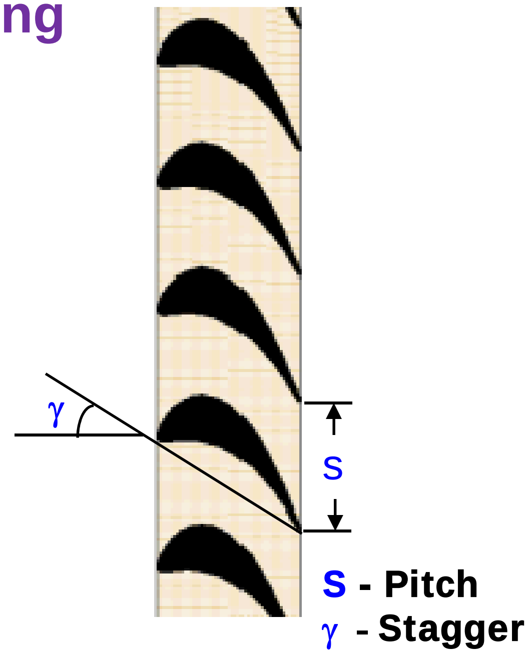
High speed rig
More complex
Detailed measurements difficult
Closer to engine condition



Linear cascade model & cascade testing



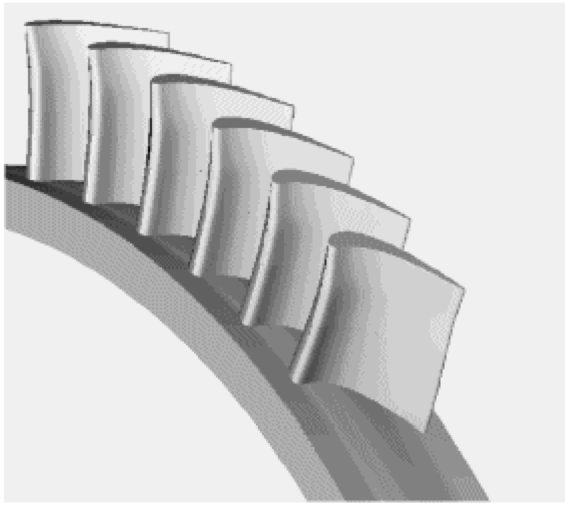
Turbine blade row



Linear Cascade model

- A linear cascade model is an array of aerofoils stacked at uniform pitch and stagger representing a section of a turbo machinery blade row.
- Linear cascade testing is a simplified experimental method for evaluating aerodynamic performance of turbo machinery aerofoils where Coriolis effects and curvilinear effects are ignored.
- The three-dimensional flows can be simplified to two-dimensional flows by using linear cascades.

Cascade tests for Axial machines and radial machines



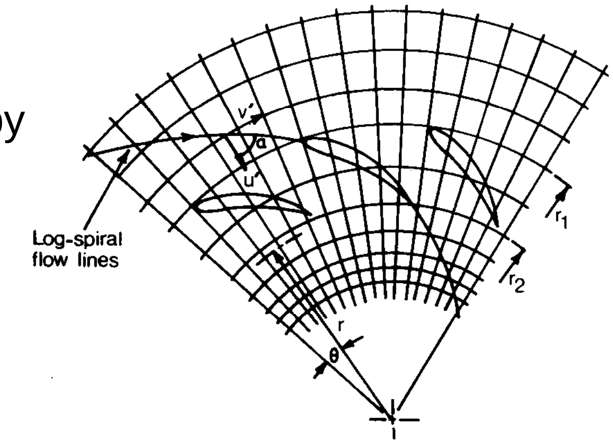
Axial machines

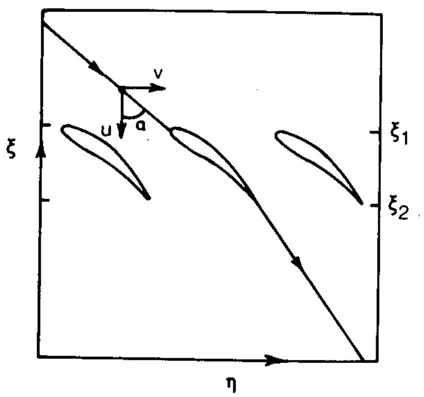
The blade row is unrolled from a cylinder by a simple transformation

$x = z, \quad y = r\,\theta$

Radial machines

Data obtained from conventional axial cascades shall be applied by conformal transformation from radial $(z = re^{i\theta})$ to axial plane $(\zeta = \xi + i\eta)$





Where,

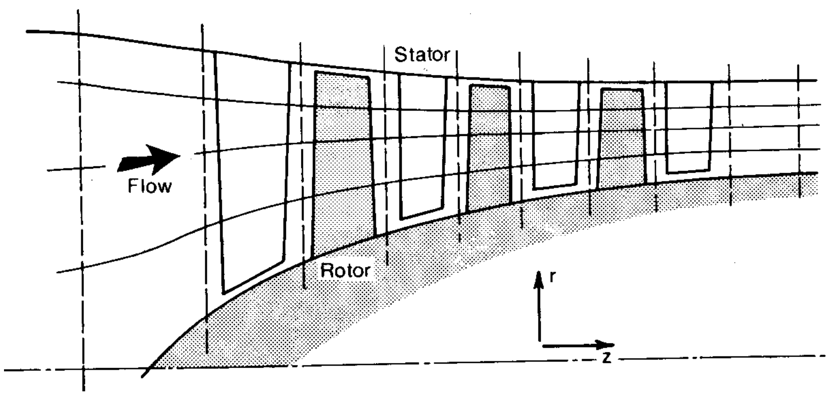
$\zeta = \ln z, \quad \xi = \ln r \quad \eta = \theta$

SIGNIFICANCE OF CASCADE TESTS

- Flow parameters such as inlet flow angle, true relative Mach number, true Reynolds number etc., can be simulated with ease
- Can provide aerodynamic performance data like blade loading / lift coefficient, profile loss / drag coefficient and flow deflection
- Easy to map pressure and velocity distributions over the aerofoils and in the passage
- Detailed studies on laminar, transition & turbulent boundary layers over turbo machinery aerofoils can be carried out
- Separation and vortex formation studies
- Local boundary layer profile and shear stress measurements over the aerofoils can also be made
- It is simple to generate data at off design conditions
- Ideal method for comparison of different profiles for the same design or in other words optimization of aerofoils
- Can provide data bank for validating CFD codes

Limitations of Cascade testing

- Curvilinear and Coriolis effects are ignored
- Predominantly a cold flow test method
- Offers no information on three dimensional flow structure
- Lack of information on unsteady flow fields
- A very difficult process while applied to radial flow machines
- Can be an expensive exercise
- Cascade test data require appropriate treatment if used for through flow analysis like stream line curvature method



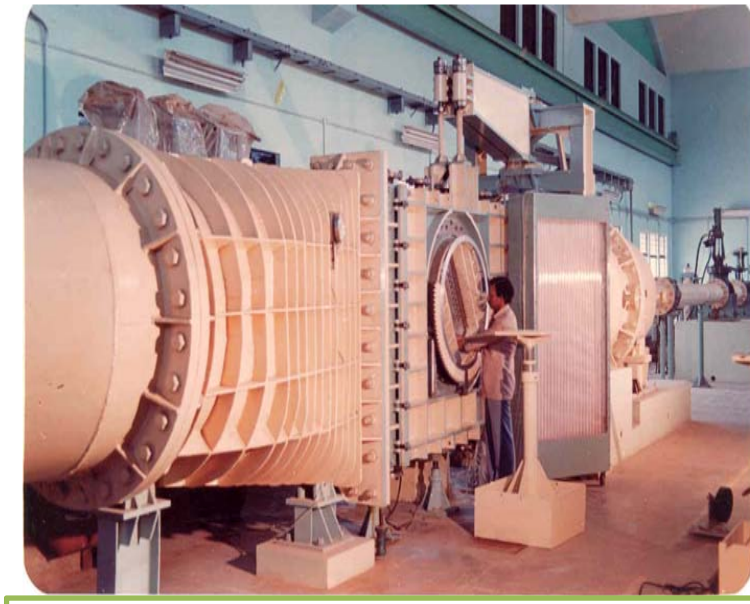
Streamlines across a multistage turbomachine

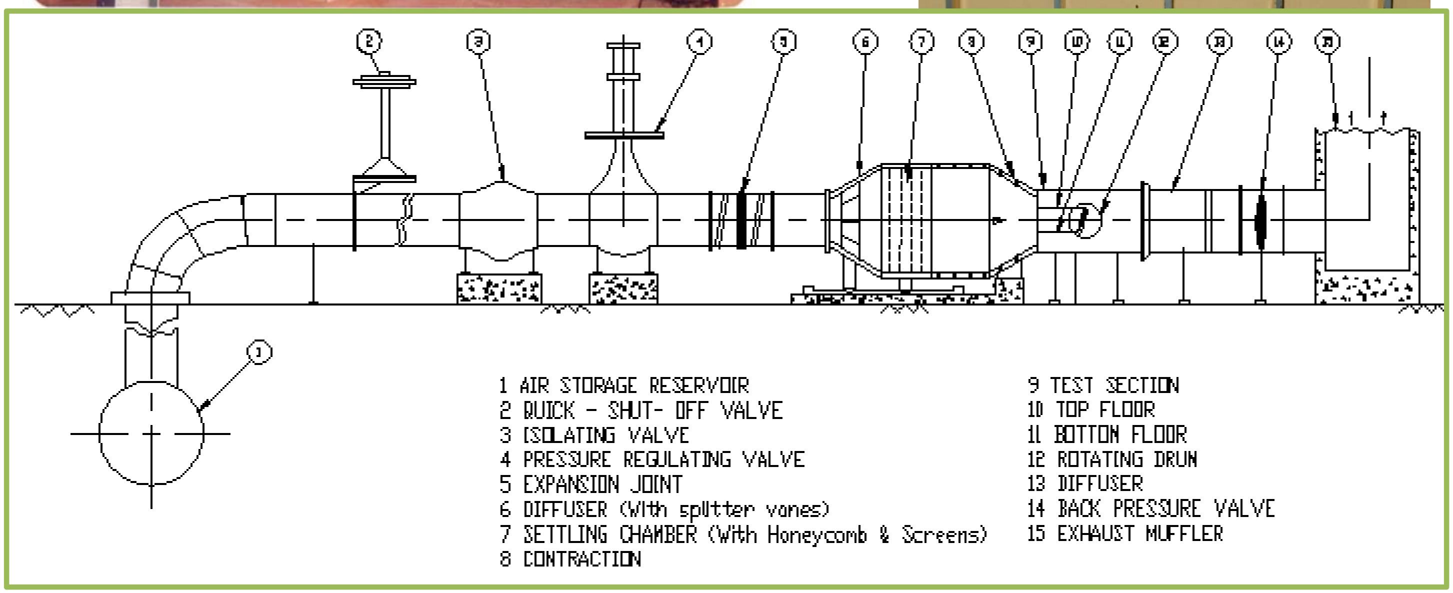
Cascade wind tunnel - Classification

1. Subsonic, transonic & supersonic
2. Blowdown & suck down
3. Open circuit & closed circuit (Variable density)
4. Medium of operation: Air, steam, combusted gas products etc.,

NAL Cascade Wind Tunnels

a) Subsonic cascade Tunnel (SCT)
b) Transonic Cascade Tunnel (TCT)





NAL TRANSONIC CASCADE TUNNEL (TCT)

NAL - TRANSONIC CASCADE TUNNEL SPECIFICATIONS

Test Section	-	153 x 500 mm*
Blade chord	-	40 to 80 mm
Probe traverse	-	220 mm in 150 seconds
Span wise traverse	-	75 mm
Air storage volume	-	2800 cubic meters
Storage pressure	-	11 atm
Total temperature	-	300 K
Mass flow (Typical)	-	5 to 15 Kg/s

* Maximum

FOR TURBINE CASCADES:

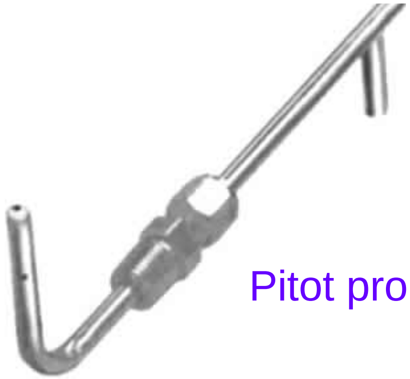
Inlet Mach number	-	Up to choking
Outlet Mach number	-	Up to 1.5
Reynolds number	-	0.3 to 2.5 millions (outlet)

FOR COMPRESSOR CASCADES:

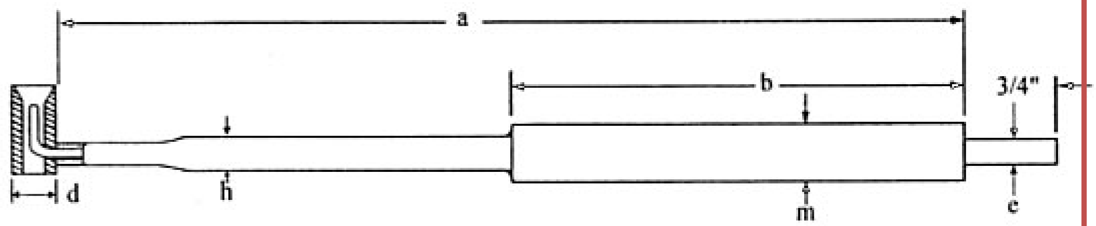
Inlet Mach number	-	Up to 0.85
Reynolds number	-	0.7 to 1.3 millions (inlet)
Reynolds number	-	0.6 to 1.1 millions(outlet)

Instrumentation for cascade tunnels

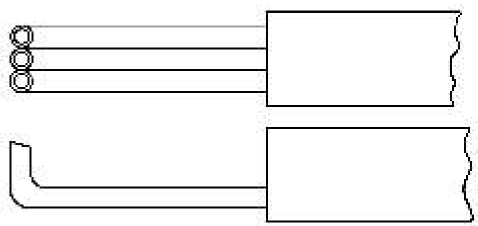
Pressure probes



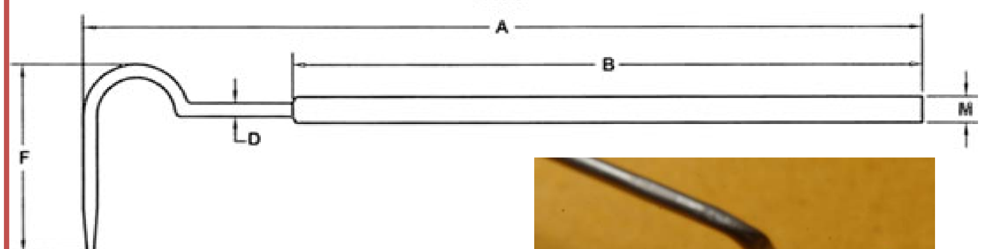
Pitot probe



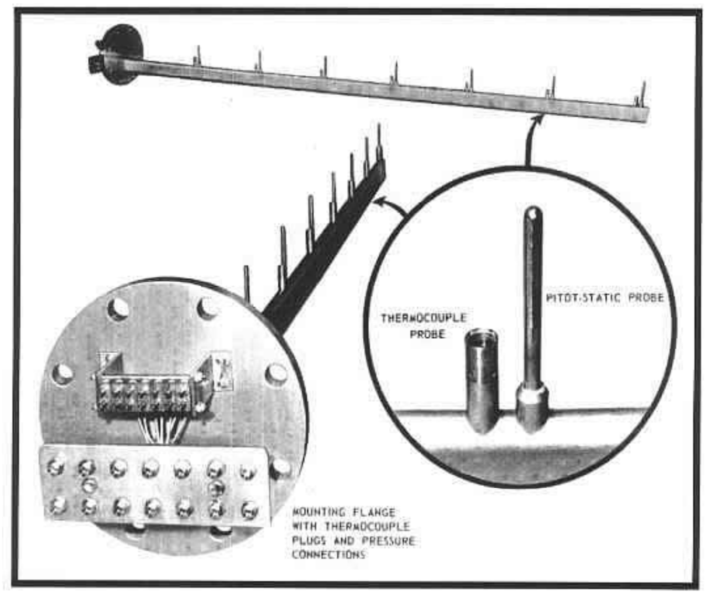
Keil probe



Three hole probe

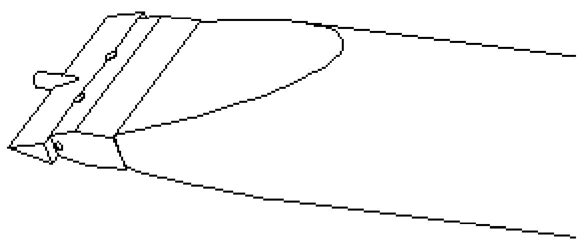


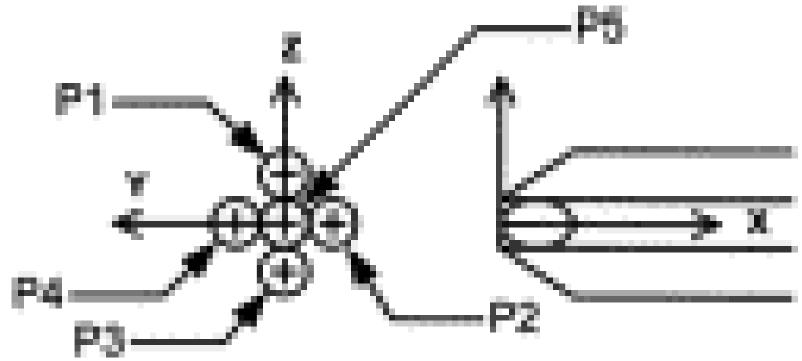
Boundary layer probe

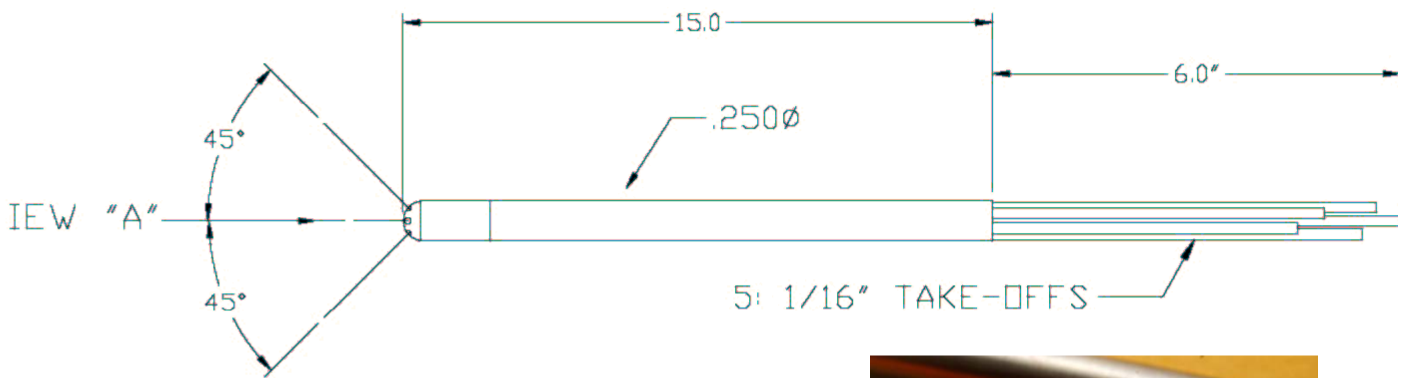


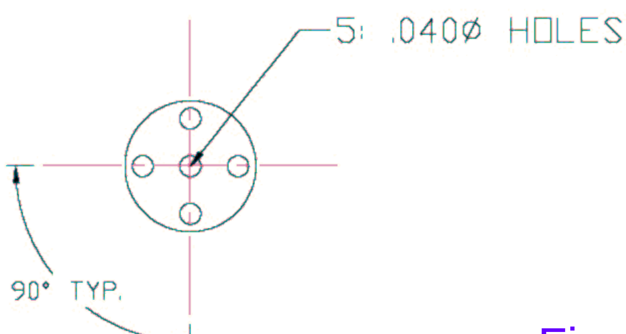
Total pressure / temperature rake

Courtesy: **M/S United sensor corporation**



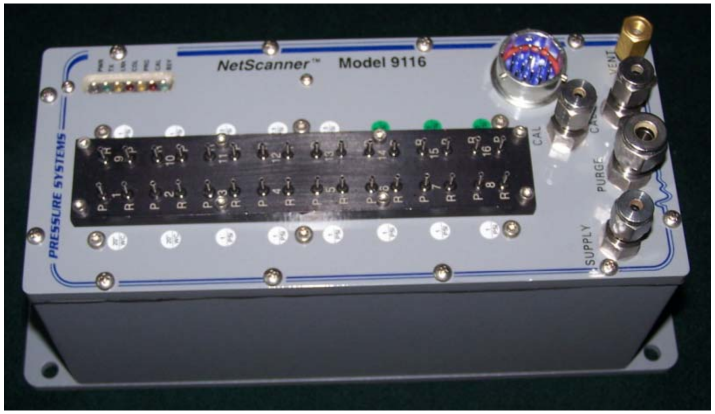






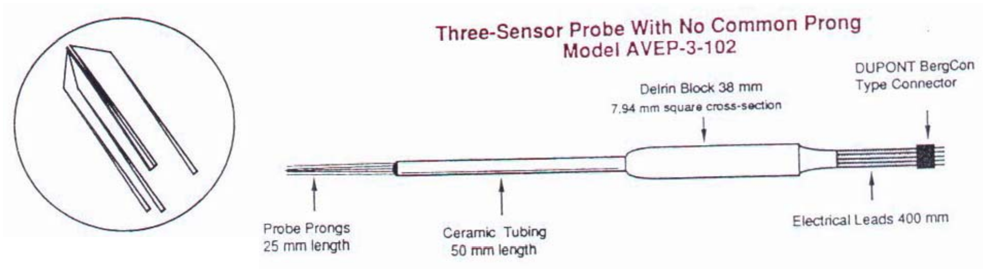
Five hole probes

ESP pressure scanner



16 channel intelligent pressure scanner

Kulite pressure transducer

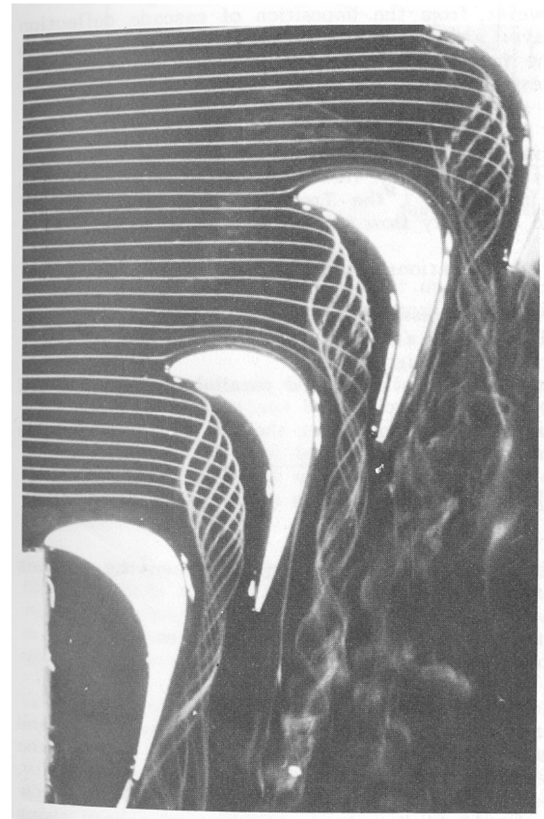


Three sensor hot wire probe

Courtesy: **M/S Scanivalve corporation, Kulite & Dantec**

Flow visualization techniques for cascade tunnels

- Smoke flow visualization
- Tuft flow visualization
- Oil flow visualization
- Schlieren technique
- Background Oriented Schlieren technique
- Interferograms
- Particle image velocimetry
- LASER Doppler Velocimetry

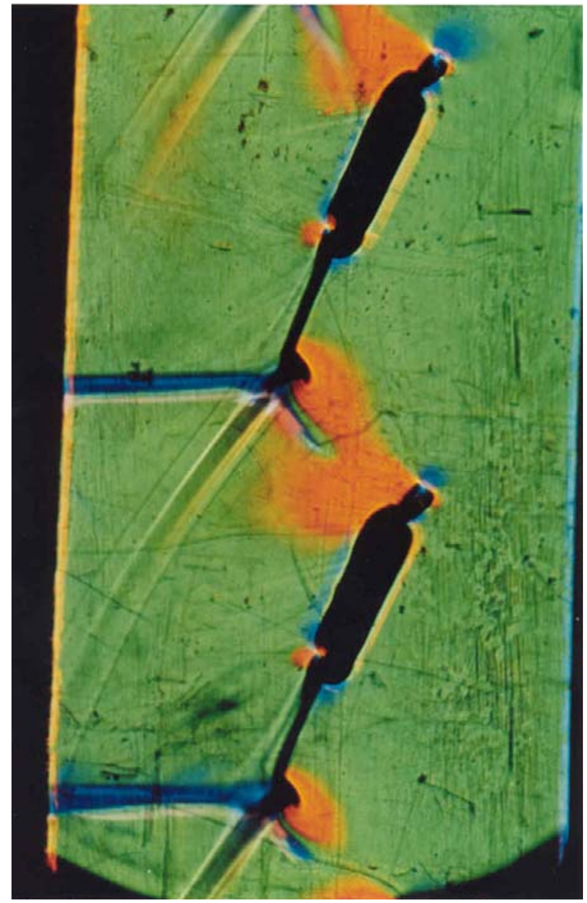


SMOKE FLOW VISUALIZATION OVER A TURBINE CASCADE

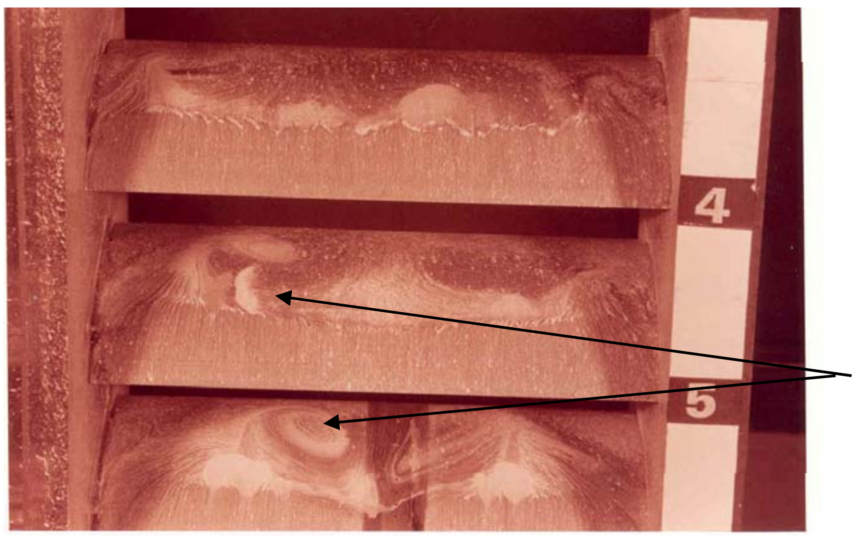
Fig. 184. Interferogram of flow through a turbine cascade with separation.

Fig. 185. Interferogram of flow through a turbine cascade without separation.

INTERFEROGRAM OF A TURBINE CASCADE



SCHLIEREN PHOTOGRAPH OF A TURBINE ROTOR CASCADE



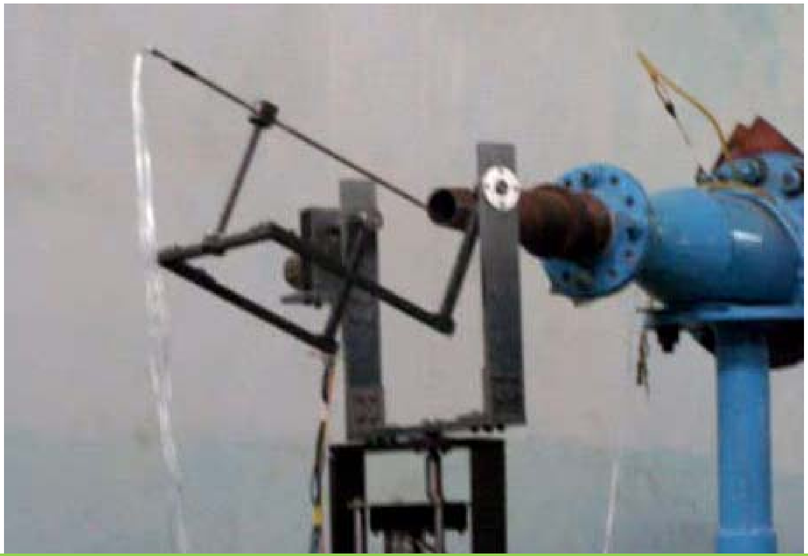
OIL FLOW VISUALIZATION ON A TURBINE CASCADE

CALIBRATION OF PRESSURE PROBES

- Combined pressure probes are used for loss (fom total pressure) and flow deflection measurements during cascade tests

- These probes have to be calibrated as they are employed in non-nulling mode

FACILITIES AT NAL FOR CALIBRATING PRESSURE PROBES



A straight 5-hole 3D probe calibrated in the new facility

Induction tunnel

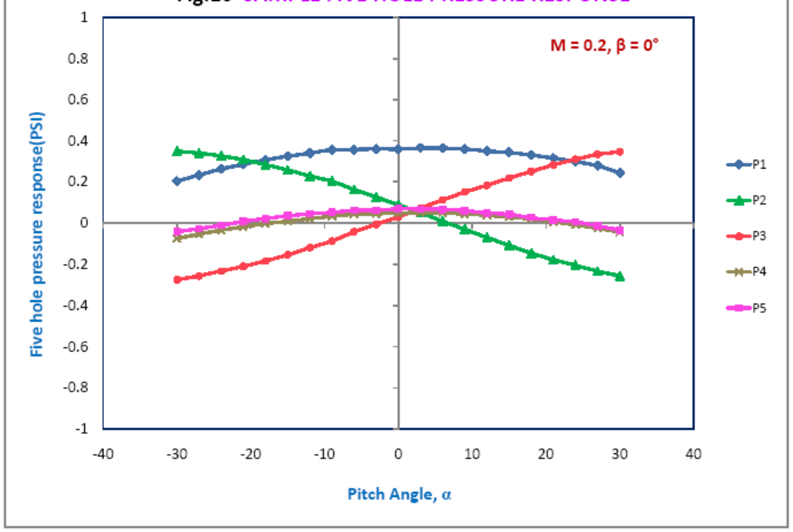


Fig.10 SAMPLE FIVE HOLE PRESSURE RESPONSE

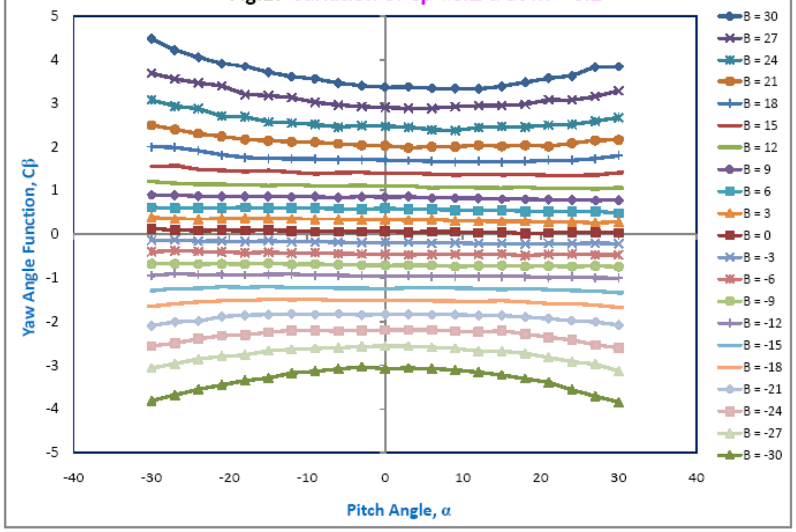


Fig.17 Variation of Cβ with α at M = 0.2

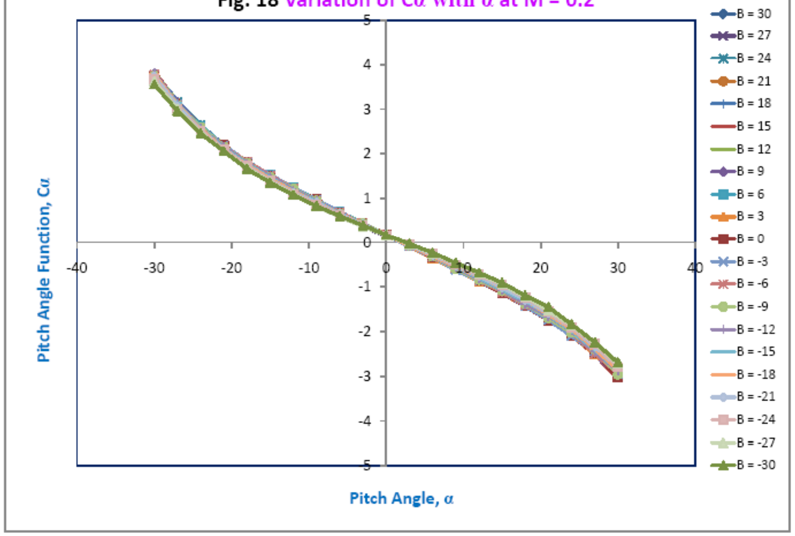
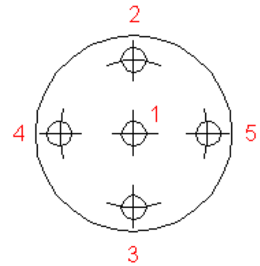
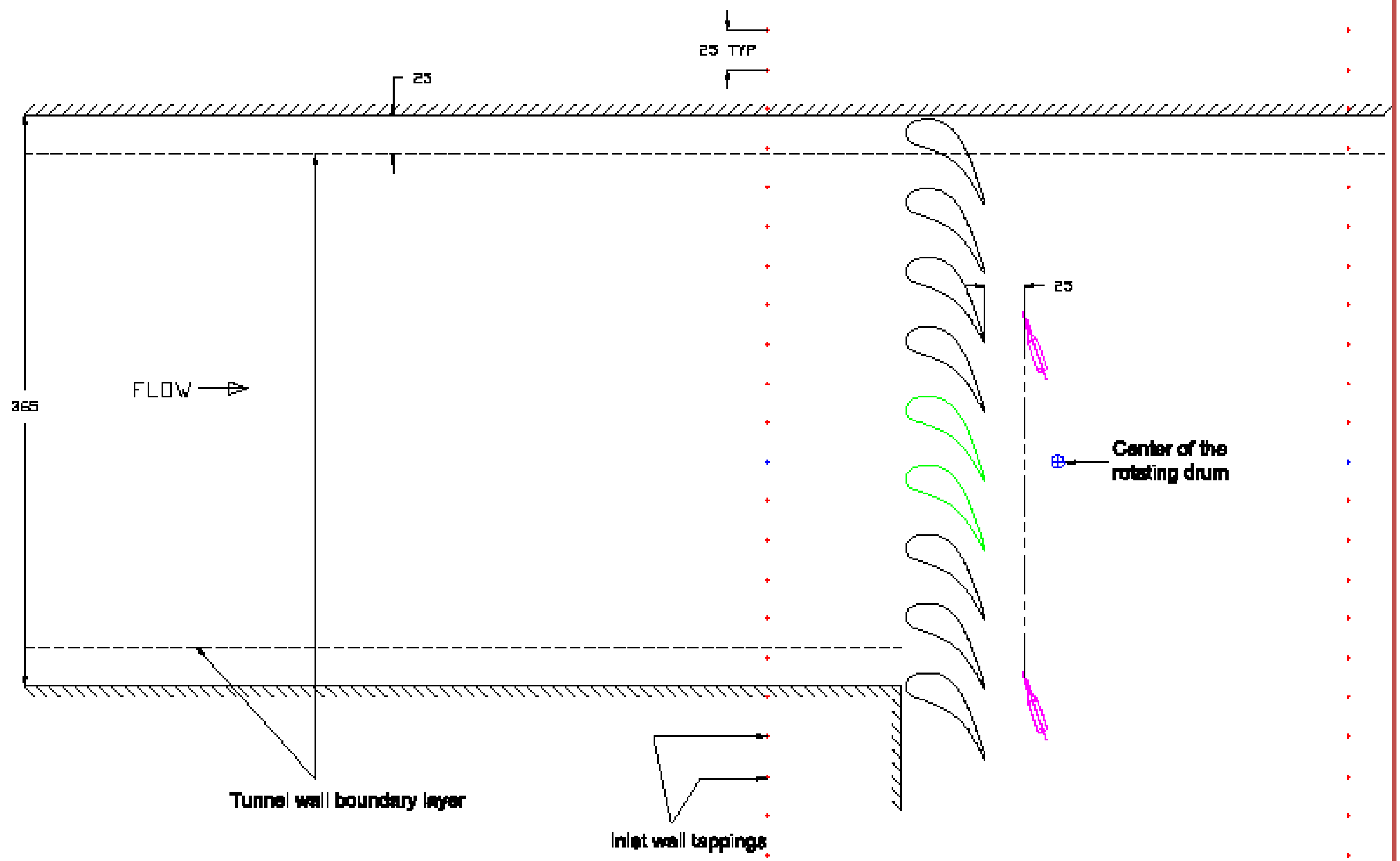


Fig. 18 Variation of Cα with α at M = 0.2

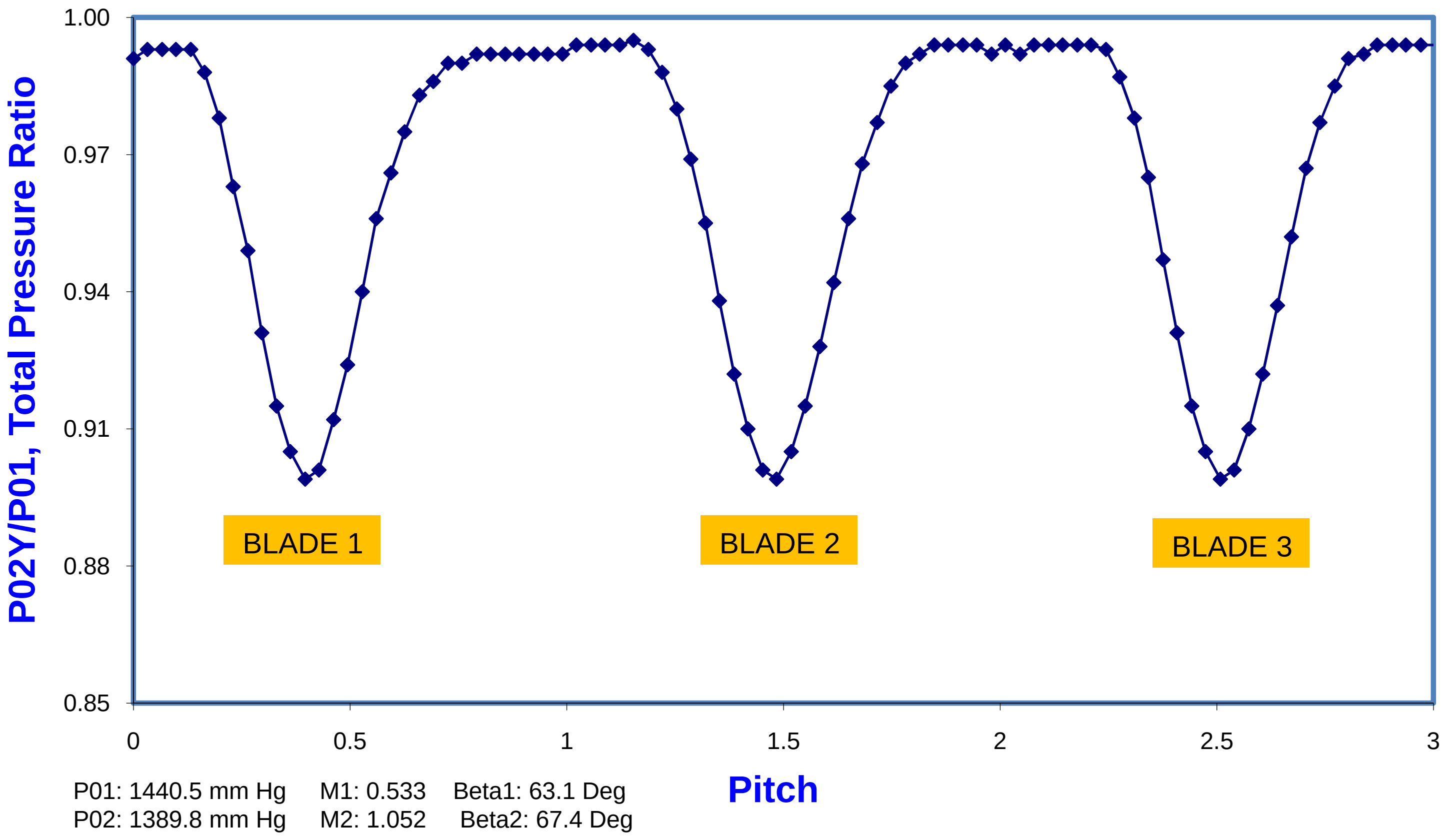


SAMPLE CALIBRATION CURVES OF A FIVE HOLE 3D PROBE



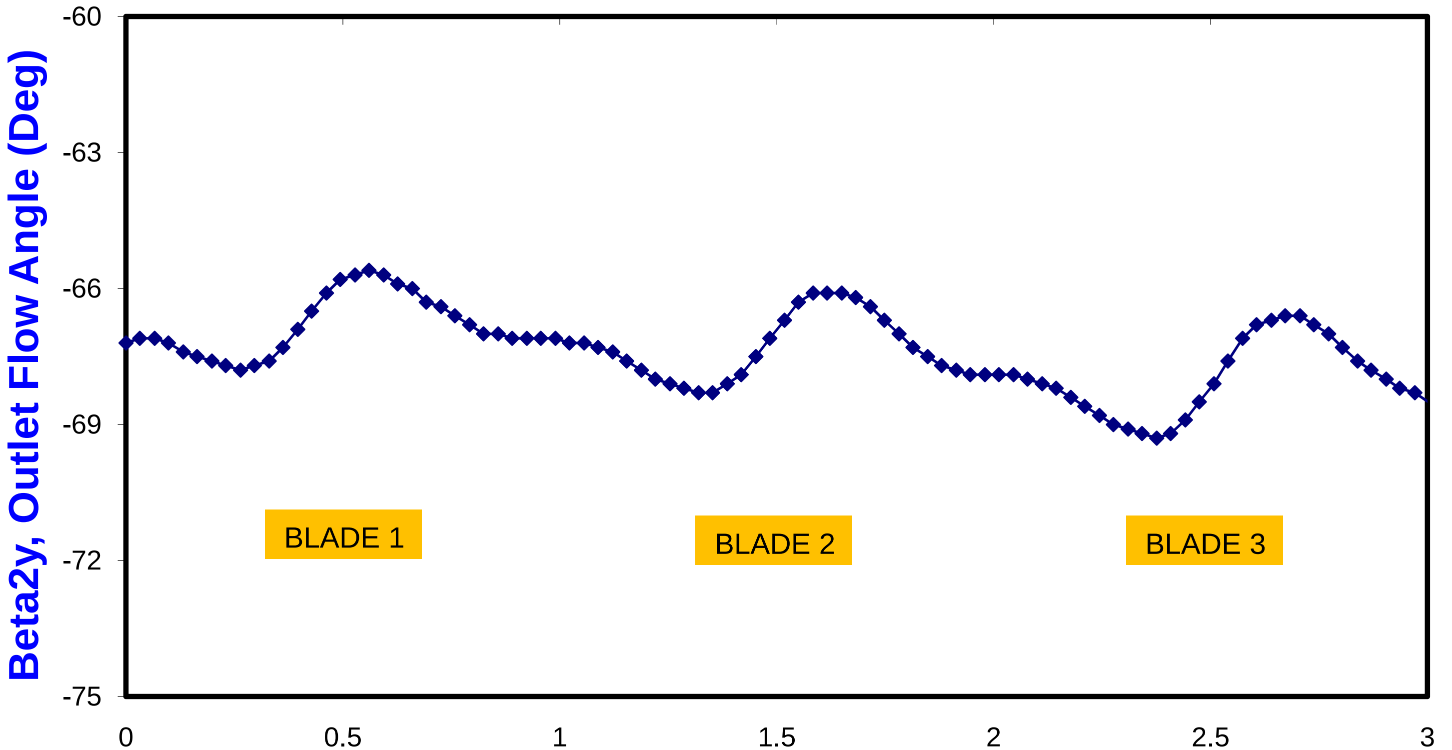
SCHEMATIC OF A TURBINE NOZZLE CASCADE IN NAL TRANSONIC CASCADE TUNNEL

Typical Wake Traverse of a Transonic Gas Turbine Stator Cascade



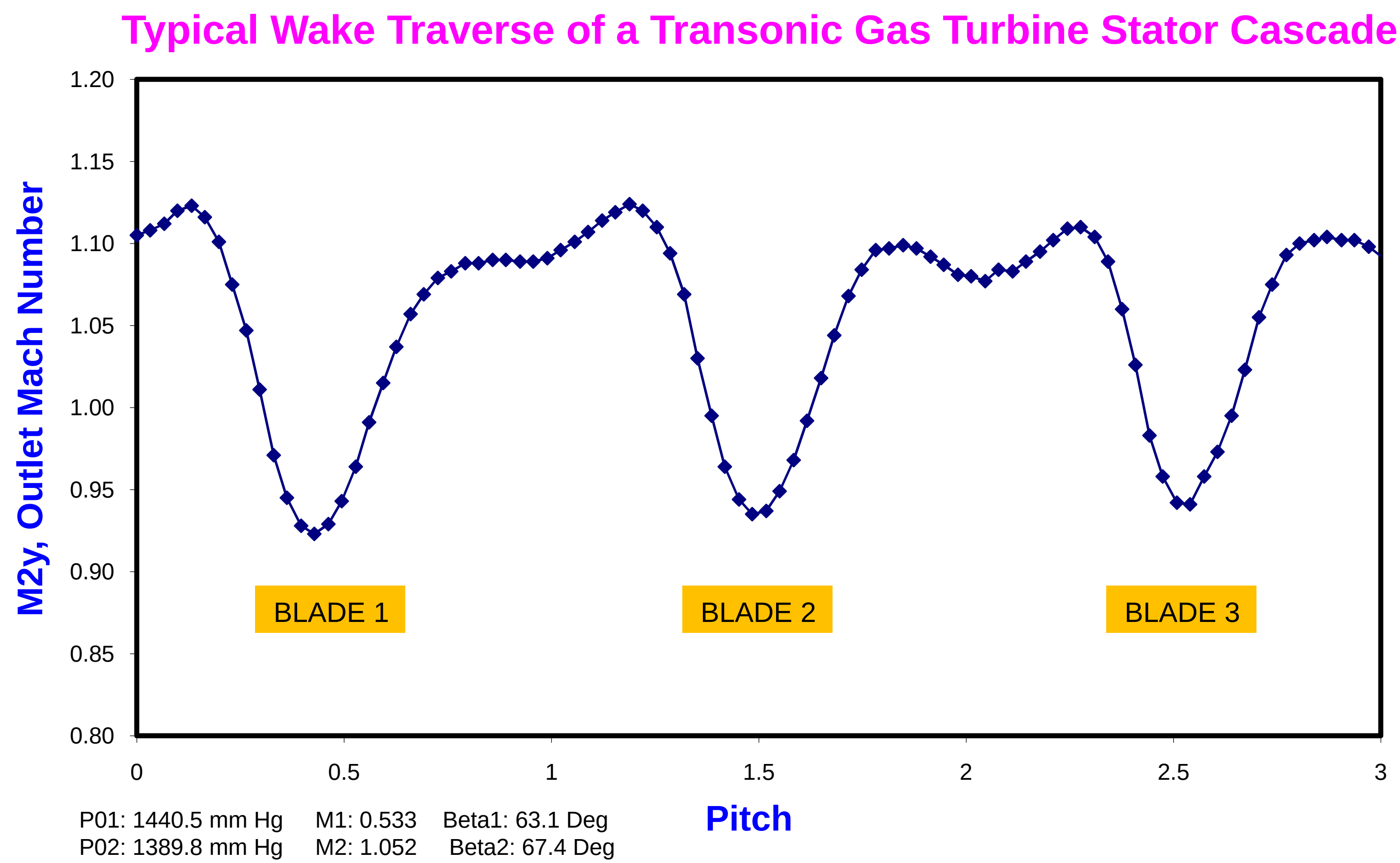
VARIATION OF TOTAL PRESSURE RATIO WITH PROBE TRAVERSE

Typical Wake Traverse of a Transonic Gas Turbine Stator Cascade

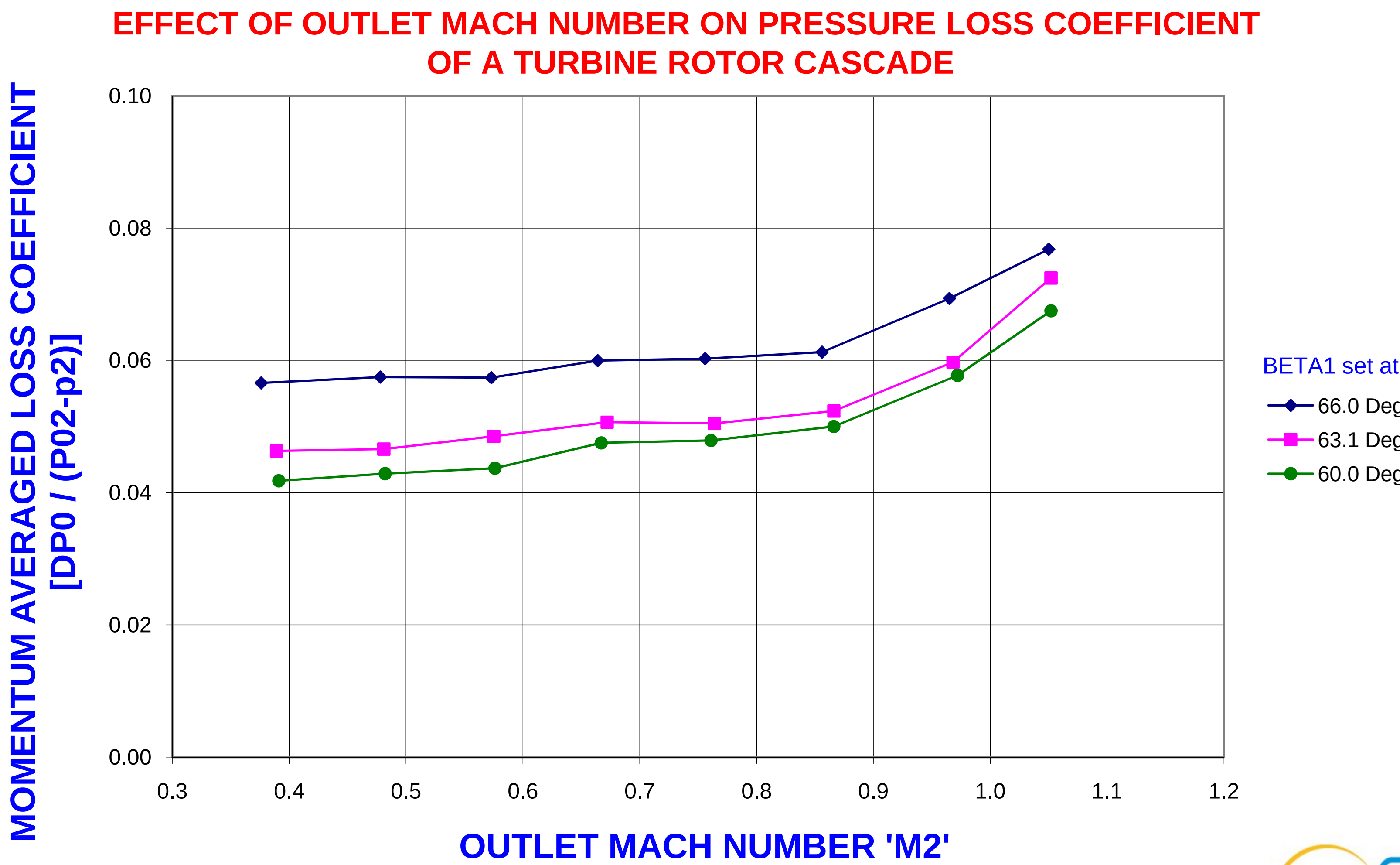


P01: 1440.5 mm Hg M1: 0.533 Beta1: 63.1 Deg
P02: 1389.8 mm Hg M2: 1.052 Beta2: 67.4 Deg

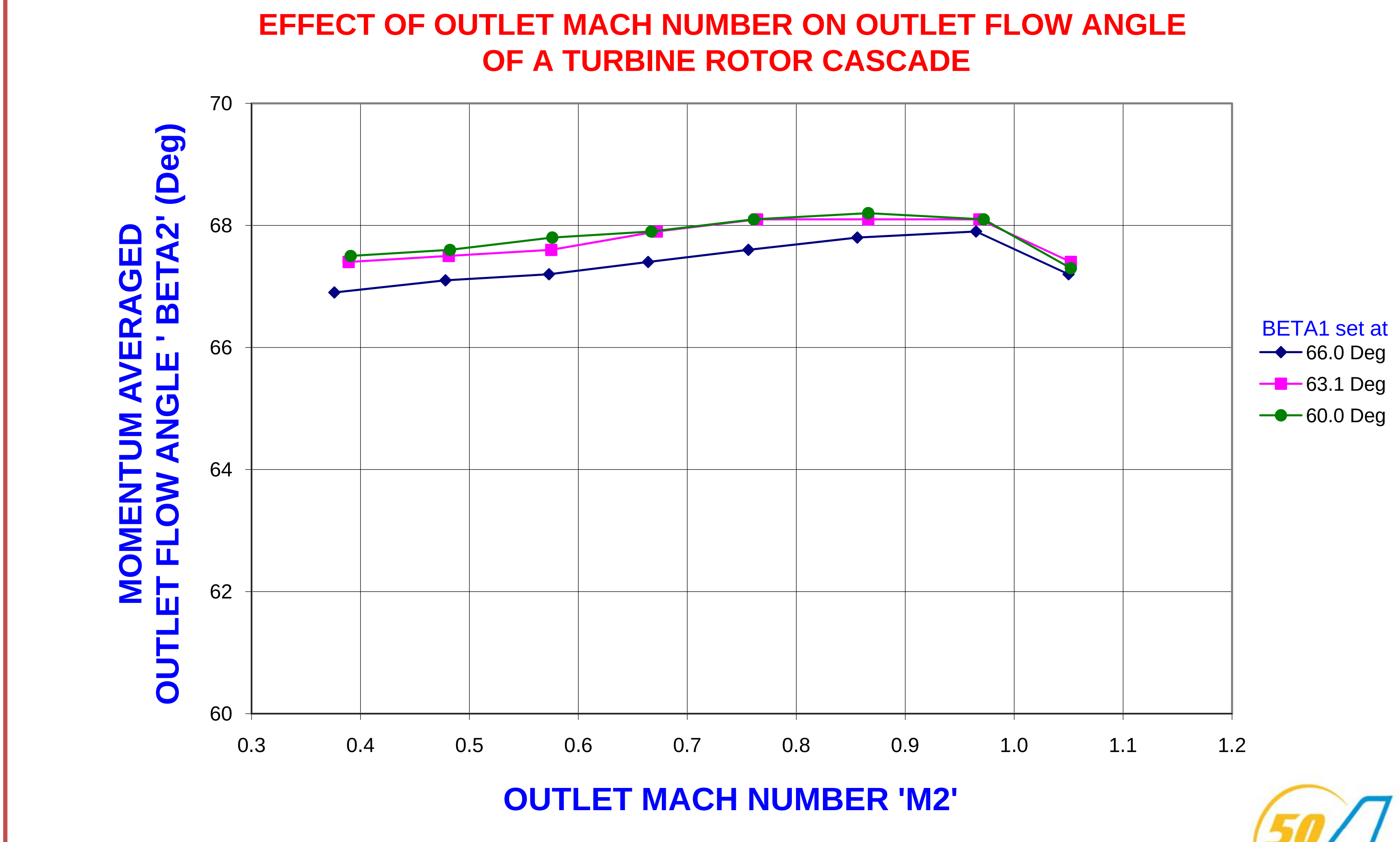
VARIATION OF OUTLET FLOW ANGLE WITH PROBE TRAVERSE

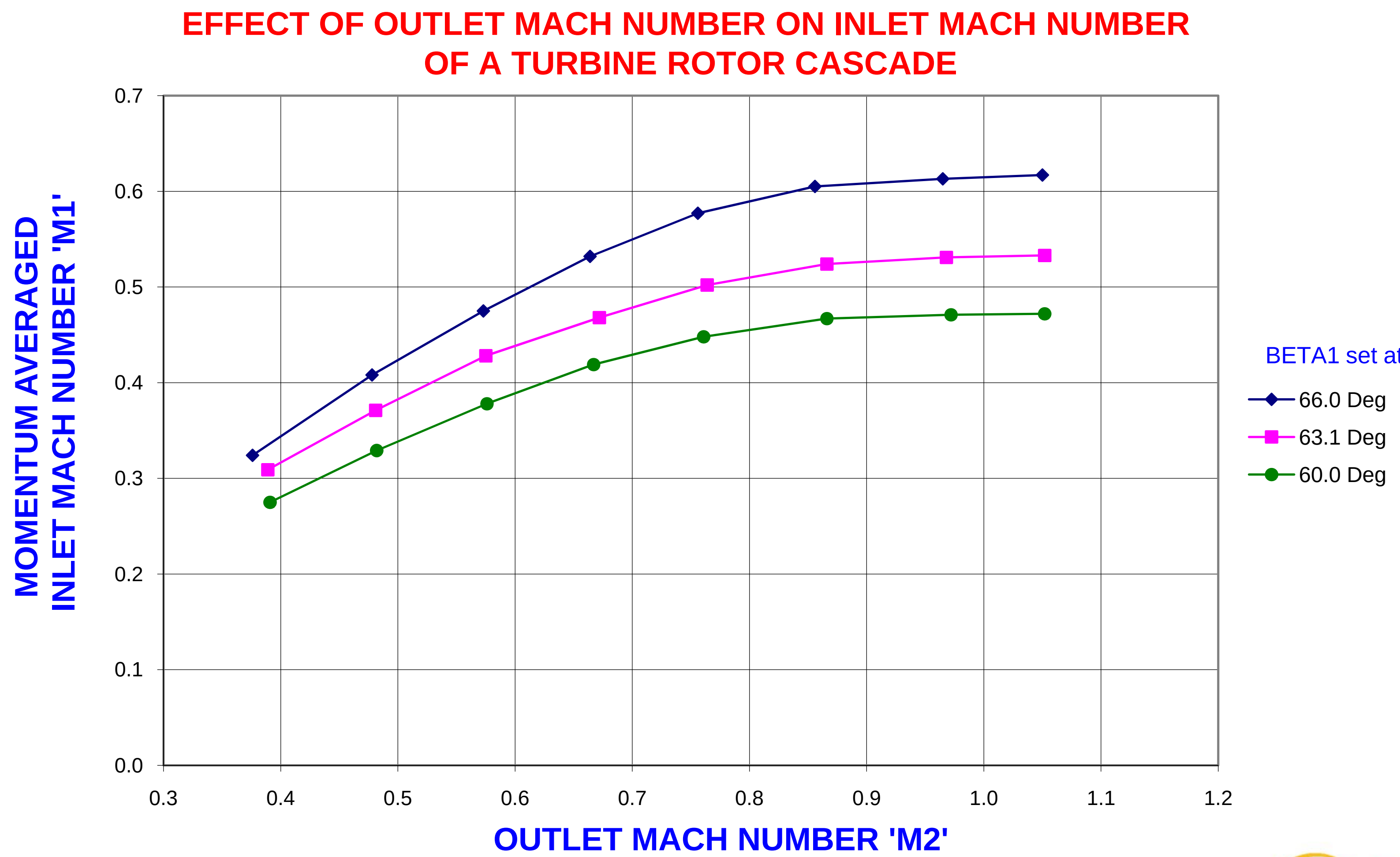


VARIATION OF OUTLET MACH NUMBER WITH PROBE TRAVERSE

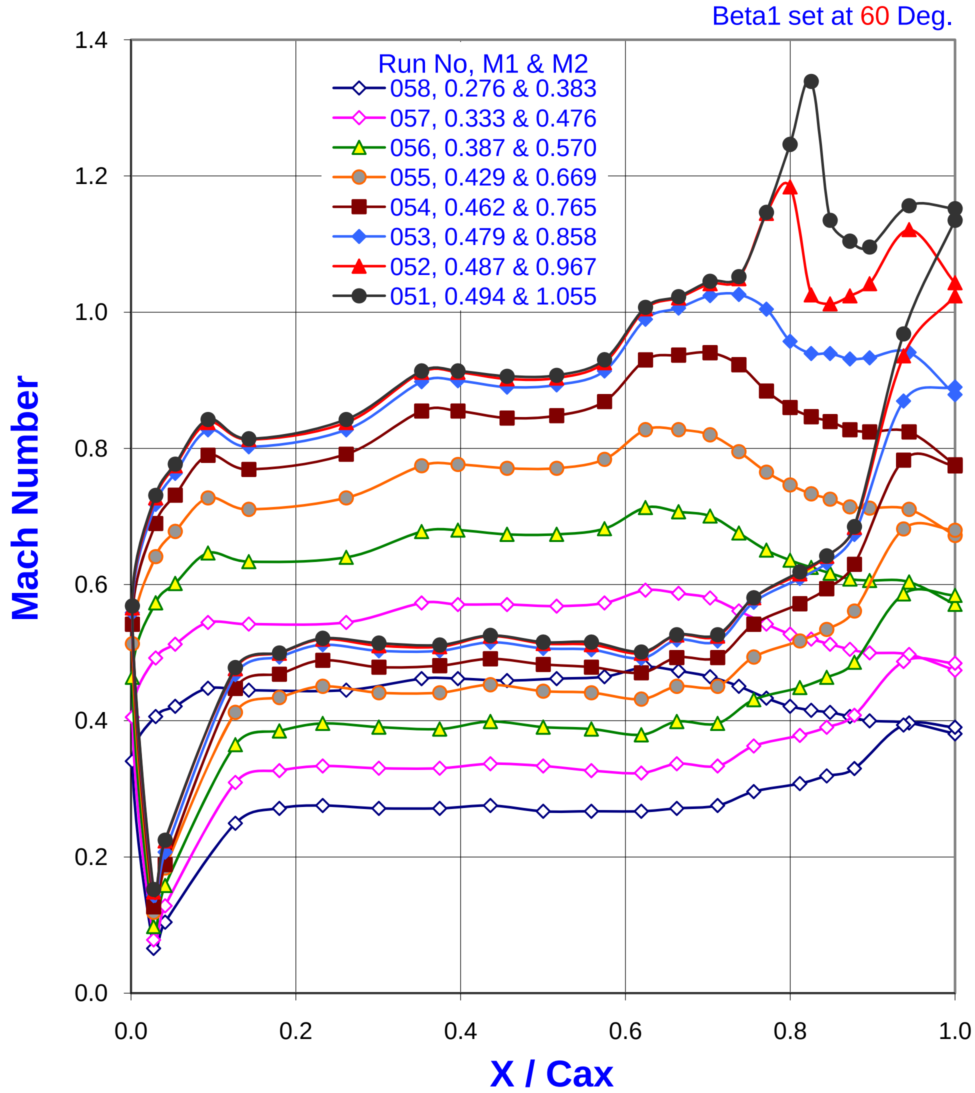


EFFECT OF OUTLET MACH NUMBER ON PRESSURE LOSS COEFFICIENT
OF A TURBINE ROTOR CASCADE
MOMENTUM AVERAGED LOSS COEFFICIENT
[DP0 / (P02-p2)]
0.10
0.08
0.06
0.04
0.02
0.00
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
OUTLET MACH NUMBER 'M2'
BETA1 set at
66.0 Deg
63.1 Deg
60.0 Deg

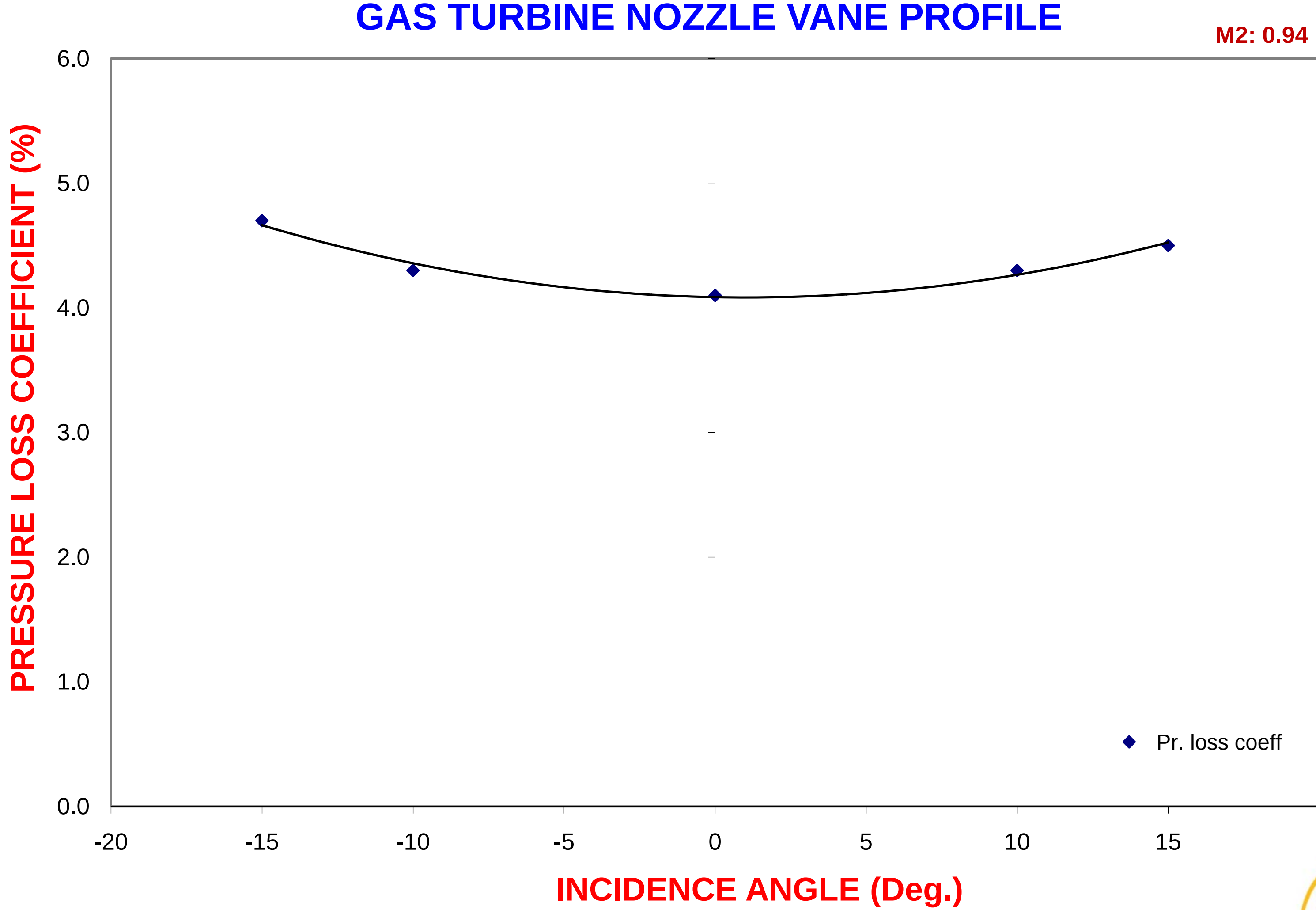

EFFECT OF OUTLET MACH NUMBER ON OUTLET FLOW ANGLE
OF A TURBINE ROTOR CASCADE
MOMENTUM AVERAGED
OUTLET FLOW ANGLE ' BETA2' (Deg)
70
68
66
64
62
60
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
OUTLET MACH NUMBER 'M2'
BETA1 set at
66.0 Deg
63.1 Deg
60.0 Deg

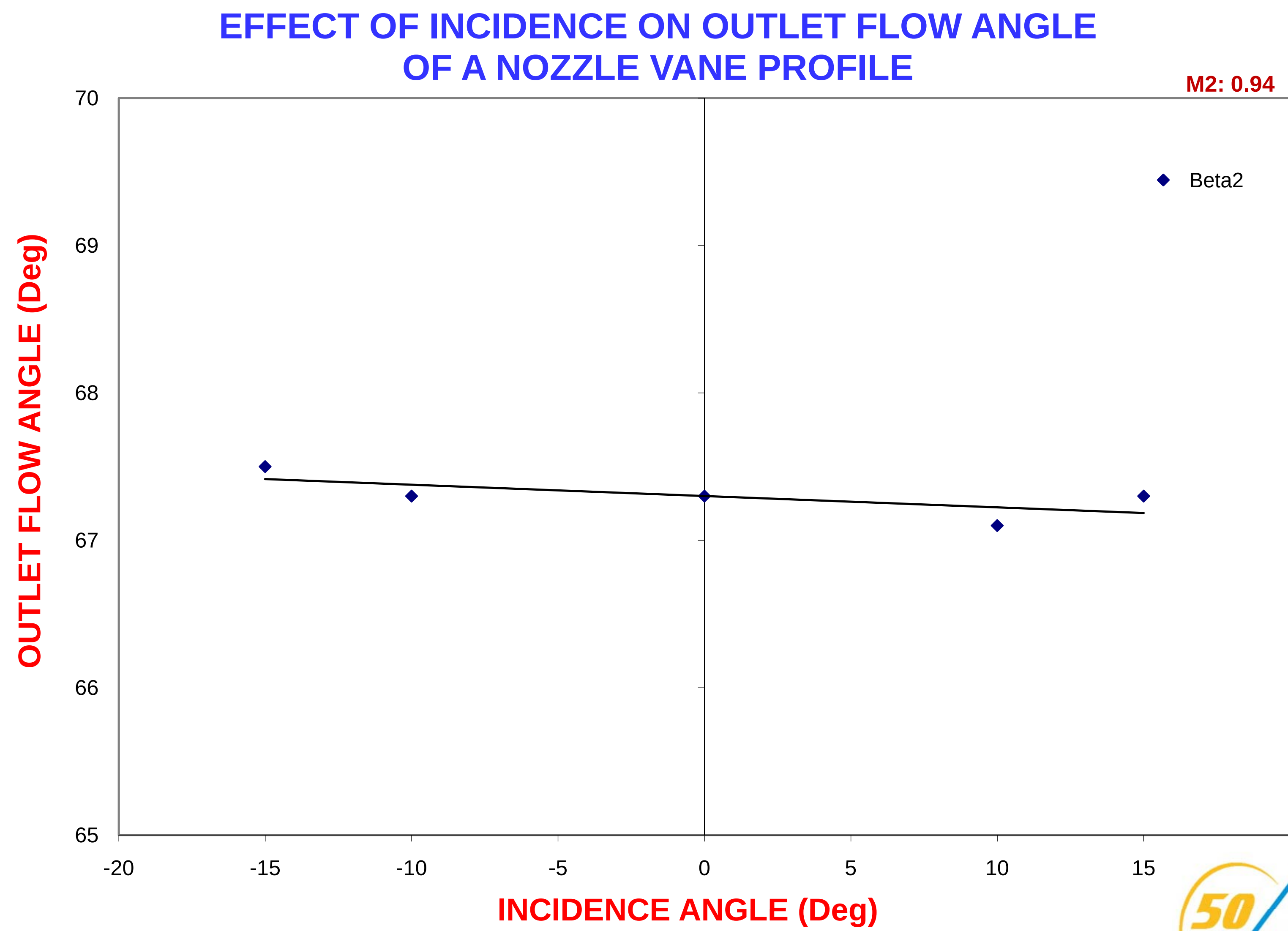

EFFECT OF OUTLET MACH NUMBER ON INLET MACH NUMBER
OF A TURBINE ROTOR CASCADE
MOMENTUM AVERAGED
INLET MACH NUMBER 'M1'
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
OUTLET MACH NUMBER 'M2'
BETA1 set at
66.0 Deg
63.1 Deg
60.0 Deg

EFFECT OF OUTLET MACH NUMBER ON SURFACE MACH NUMBER DISTRIBUTION OF A GAS TURBINE PROFILE

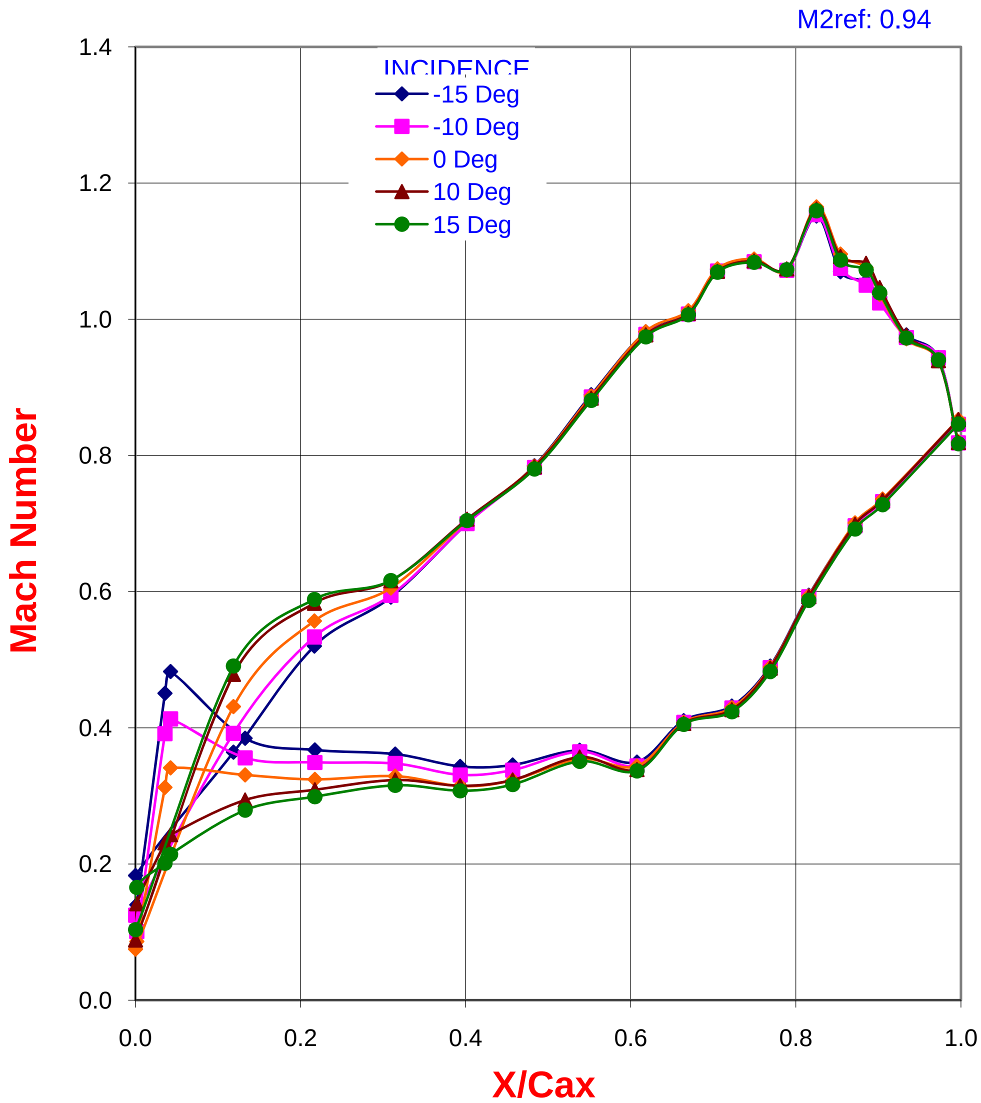


EFFECT OF INCIDENCE ON PRESSURE LOSS COEFFICIENT OF A GAS TURBINE NOZZLE VANE PROFILE




EFFECT OF INCIDENCE ON OUTLET FLOW ANGLE
OF A NOZZLE VANE PROFILE
M2: 0.94
Beta2
OUTLET FLOW ANGLE (Deg)
INCIDENCE ANGLE (Deg)
70
69
68
67
66
65
-20
-15
-10
-5
0
5
10
15

Effect of Incidence on Surface Mach Number Distribution of a Gas Turbine Nozzle Vane Profile



Effect of free stream turbulence

An experimental study was conducted in a two-dimensional linear cascade, focusing on the suction surface of a low pressure turbine blade. Flow Reynolds numbers, based on exit velocity and suction length, have been varied from 50,000 to 300,000. The freestream turbulence intensity was varied from 1.1 to 8.1 percent. Separation was observed at all test Reynolds numbers. Increasing the flow Reynolds number, without changing freestream turbulence, resulted in a rearward movement of the onset of separation and shrinkage of the separation zone. Increasing the freestream turbulence intensity, without changing Reynolds number, resulted in shrinkage of the separation region on the suction surface. The influences on the blade's wake from altering freestream turbulence and Reynolds number are also documented. It is shown that width of the wake and velocity defect rise with a decrease in either turbulence level or chord Reynolds number.

"An Experimental Investigation of the Effect of Freestream Turbulence on the Wake of a Separated Low-Pressure Turbine Blade at Low Reynolds Numbers"
Murawski CG, Vafai K J. **Fluids Eng. -- June 2000 -- Volume 122, Issue 2, 431**

Effect of free stream turbulence

Tip clearance losses represent a major efficiency penalty of turbine blades. This paper describes the effect of tip clearance on the aerodynamic characteristics of an unshrouded axial-flow turbine cascade under very low Reynolds number conditions. The Reynolds number based on the true chord length and exit velocity of the turbine cascade was varied from 4.4×10^4 to 26.6×10^4 by changing the velocity of fluid flow. The freestream turbulence intensity was varied between 0.5% and 4.1% by modifying turbulence generation sheet settings. Three-dimensional flow fields at the exit of the turbine cascade were measured both with and without tip clearance using a five-hole pressure probe. Tip leakage flow generated a large high total pressure loss region. Variations in the Reynolds number and freestream turbulence intensity changed the distributions of three-dimensional flow, but had no effect on the mass-averaged tip clearance loss of the turbine cascade.

"Effects of Reynolds Number and Freestream Turbulence on Turbine Tip Clearance Flow"
Takayuki Matsunuma **J. Turbomach. -- January 2006 -- Volume 128, Issue 1, 166**

Effect of free stream turbulence

An experimental and analytical study has been performed on the effect of Reynolds number and free-stream turbulence on boundary layer transition location on the suction surface of a controlled diffusion airfoil (CDA). The experiments were conducted in a rectilinear cascade facility at Reynolds numbers between 0.7 and 3.0×10^6 and turbulence intensities from about 0.7 to 4 percent. An oil streak technique and liquid crystal coatings were used to visualize the boundary layer state. For small turbulence levels and all Reynolds numbers tested, the accelerated front portion of the blade is laminar and transition occurs within a laminar separation bubble shortly after the maximum velocity near 35–40 percent of chord. For high turbulence levels (Tu>3 percent) and high Reynolds numbers, the transition region moves upstream into the accelerated front portion of the CDA blade. For those conditions, the sensitivity to surface roughness increases considerably; at Tu=4 percent, bypass transition is observed near 7–10 percent of chord. Experimental results are compared to theoretical predictions using the transition model, which is implemented in the MISES code of Youngren and Drela. Overall, the results indicate that early bypass transition at high turbulence levels must alter the profile velocity distribution for compressor blades that are designed and optimized for high Reynolds numbers.

“Effects of Reynolds Number and Free-Stream Turbulence on Boundary Layer Transition in a Compressor Cascade”
Schreiber HA etal. **J. Turbomach. -- January 2002 -- Volume 124, Issue 1, 1**

Effect of surface roughness

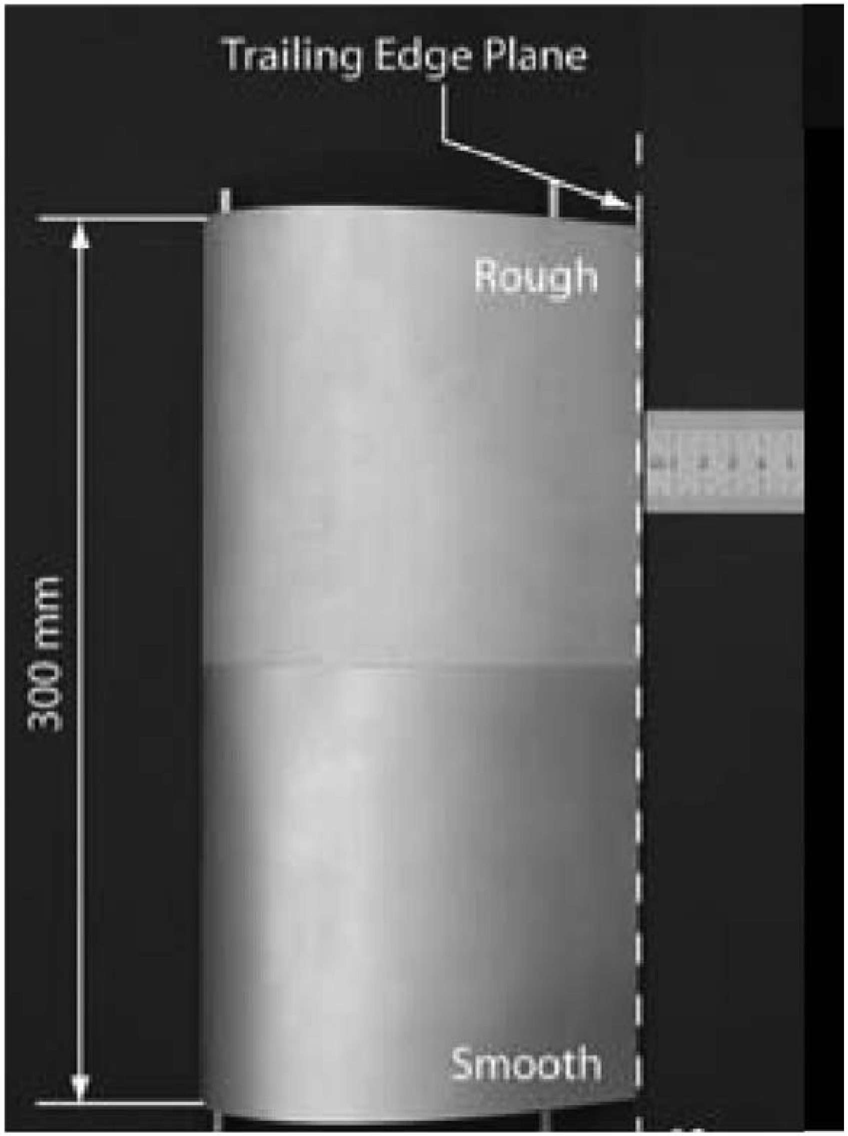
Measurements of pressure distributions, profile losses, and flow deviation were carried out on a planar turbine cascade in incompressible flow to assess the effects of partial roughness coverage of the blade surfaces. Spanwise-oriented bands of roughness were placed at various locations on the suction and pressure surfaces of the blades. Roughness height, spacing between roughness elements, and band width were varied. A computational method based on the inviscid/viscous interaction approach was also developed; its predictions were in good agreement with the experimental results. This indicates that good predictions can be expected for a variety of cascade and roughness configurations from any two-dimensional analysis that couples an inviscid method with a suitable rough surface boundary-layer analysis. The work also suggests that incorporation of the rough wall skin-friction law into a three-dimensional Navier-Stokes code would enable good predictions of roughness effects in three-dimensional situations. Roughness was found to have little effect on static pressure distribution around the blades and on deviation angle, provided that it does not precipitate substantial flow separation. Roughness on the suction surface can cause large increases in profile losses; roughness height and location of the leading edge of the roughness band are particularly important. Loss increments due to pressure-surface roughness are much smaller than those due to similar roughness on the suction surface.

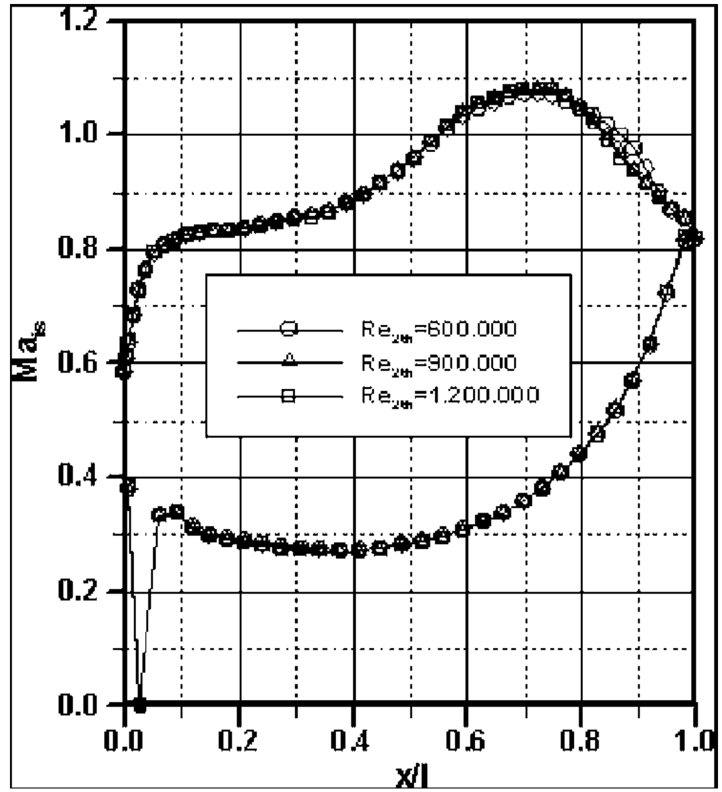
1. "Measurements and prediction of the effects of surface roughness on profile losses and deviation in a turbine cascade"
Klind RJ etal. **J. Turbomach 1998, vol. 120, pp. 20-27**

Effect of surface roughness

The aerodynamic performance of a turbine blade was evaluated via total pressure loss measurements on a linear cascade. The Reynolds number was varied from 600 000 to 1 200 000 to capture the operating regime for heavy-duty gas turbines. Four different types of surface roughness on the same profile were tested in the High Speed Cascade Wind Tunnel of the University of the German Armed Forces Munich and evaluated against a hydraulically smooth reference blade. The ratios of surface roughness to chord length for the test blade surfaces are in the range of Ra/c=7.610−06–7.910−05. The total pressure losses were evaluated from wake traverse measurements. The loss increase due to surface roughness was found to increase with increasing Reynolds number. For the maximum tested Reynolds number of Re=1 200 000 the increase in total pressure loss for the highest analysed surface roughness value of Ra=11.8 m was found to be 40% compared to a hydraulically smooth surface. The results of the measurements were compared to a correlation from literature as well as to well-documented measurements in literature. Good agreement was found for high Reynolds numbers between the correlation and the test results presented in this paper and the data available from literature.

"Surface Roughness Effects on Turbine Blade Aerodynamics"
Frank Hummel etal. **J. Turbomach JULY 2005, Vol. Copyright © 2005 by ASME 127 / 453**

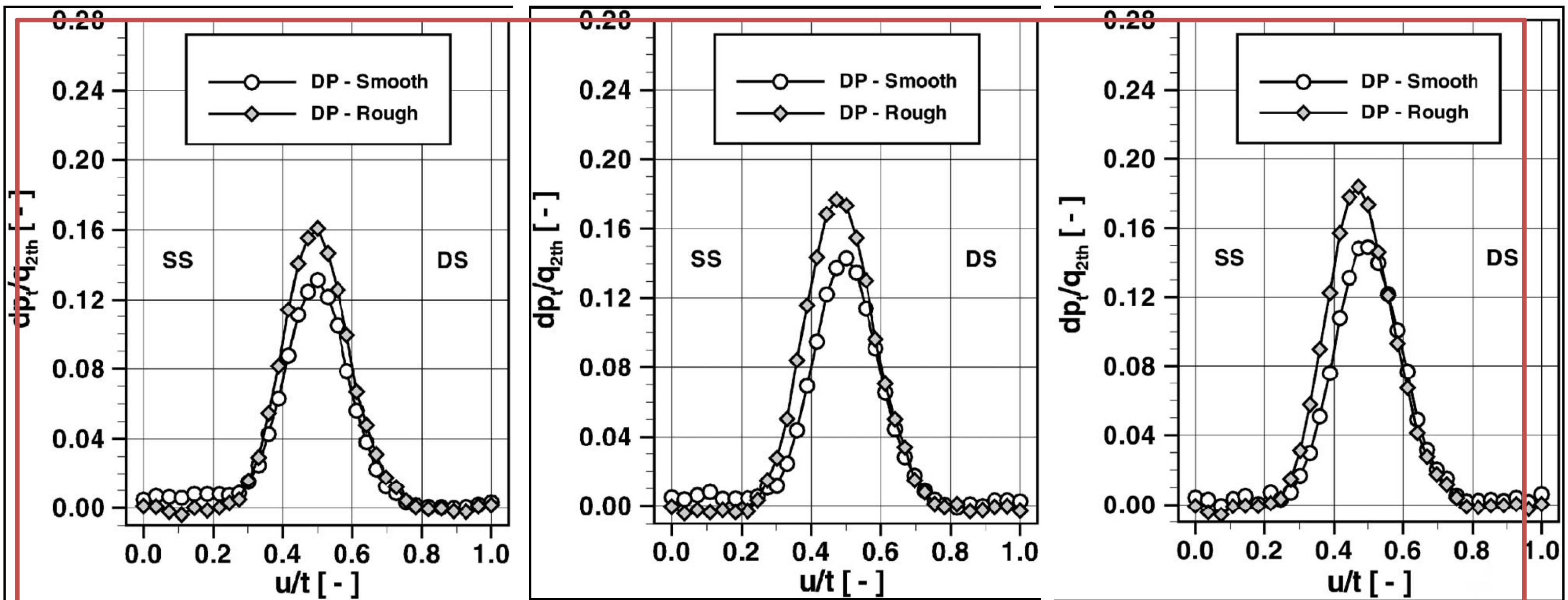




Surface isentropic Mach number distribution for β1=133.3 deg, Ma2,th=0.85 in dependence on Reynolds number

Courtesy:

Frank Hummel etal. **J. Turbomach JULY 2005, Vol. Copyright © 2005 by ASME 127 / 453**



Re2,th=600 000. Re2,th=900 000. Re2,th=1200 000.

Total pressure loss from wake traverse measurements of a double Pitot probe for test blade, rough part compared to smooth part. Ma2,th=0.75, β1=133.3°

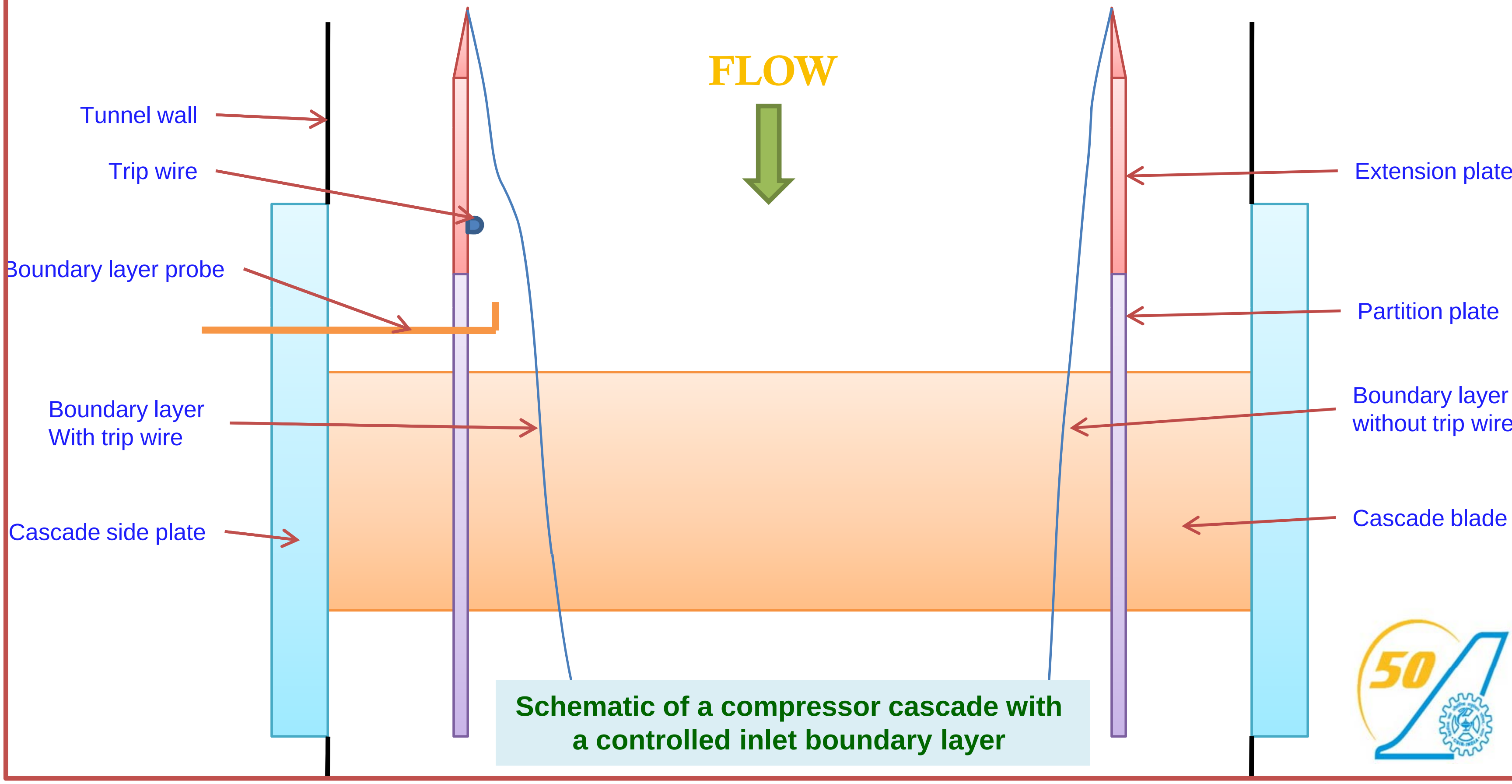
Courtesy:

Frank Hummel etal. **J. Turbomach JULY 2005, Vol. Copyright © 2005 by ASME 127**

EFFECT OF INLET BOUNDARY LAYERS

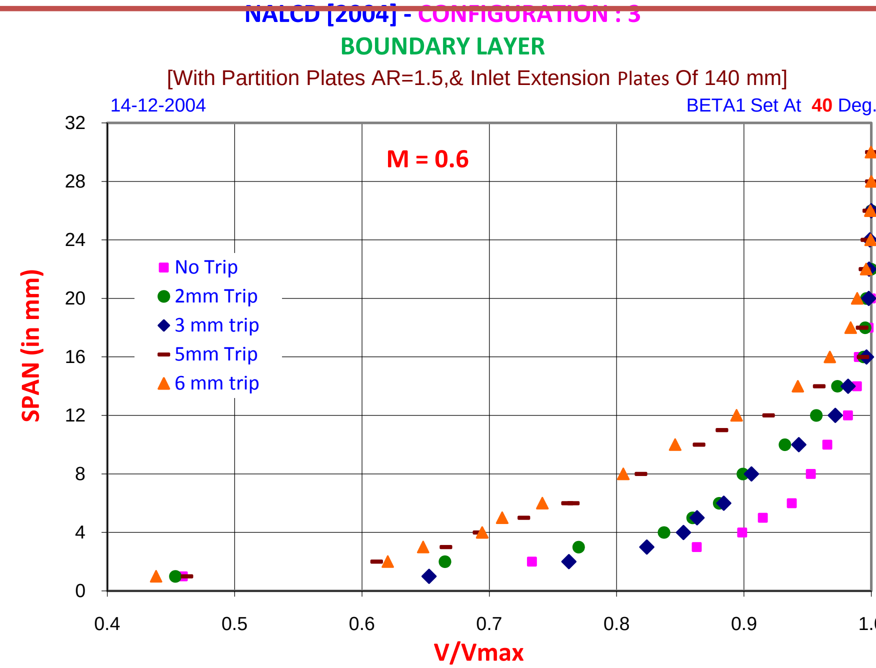
Motivation: To study the performance of compressor aerofoil sections near the walls with the influence of boundary layers and secondary flows.

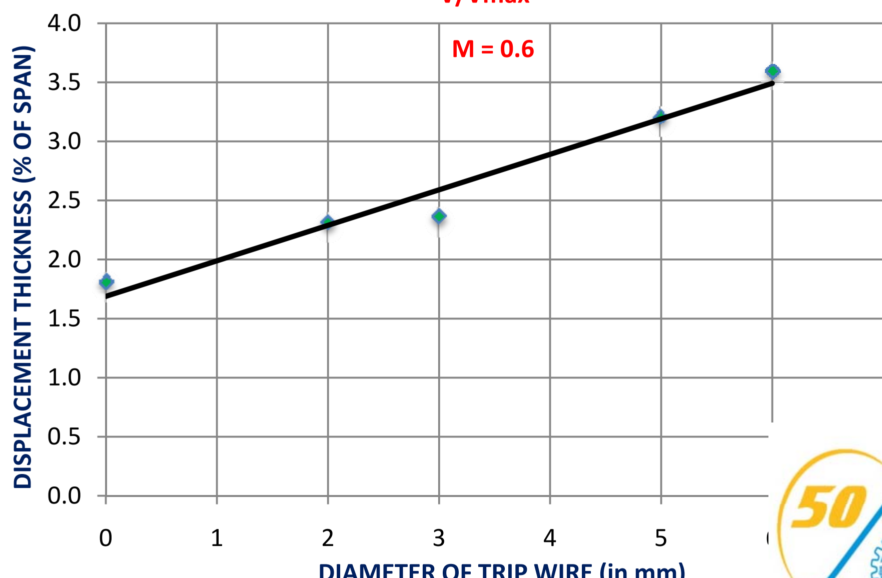
Use of flat plates (extension plate) and trip wires to generate boundary layers with displacement thickness of 1% & 3% of span



Schematic of a compressor cascade with a controlled inlet boundary layer

EFFECT OF INLET BOUNDARY LAYERS





A CDA compressor cascade with flat extension plate and trip wire

EFFECT OF TRAILING EDGE GEOMETRY

COMPARISON OF RESULTS (RM2-PROFILE)

Round Trailing Edge & Cut Trailing edge

At Design Incidence

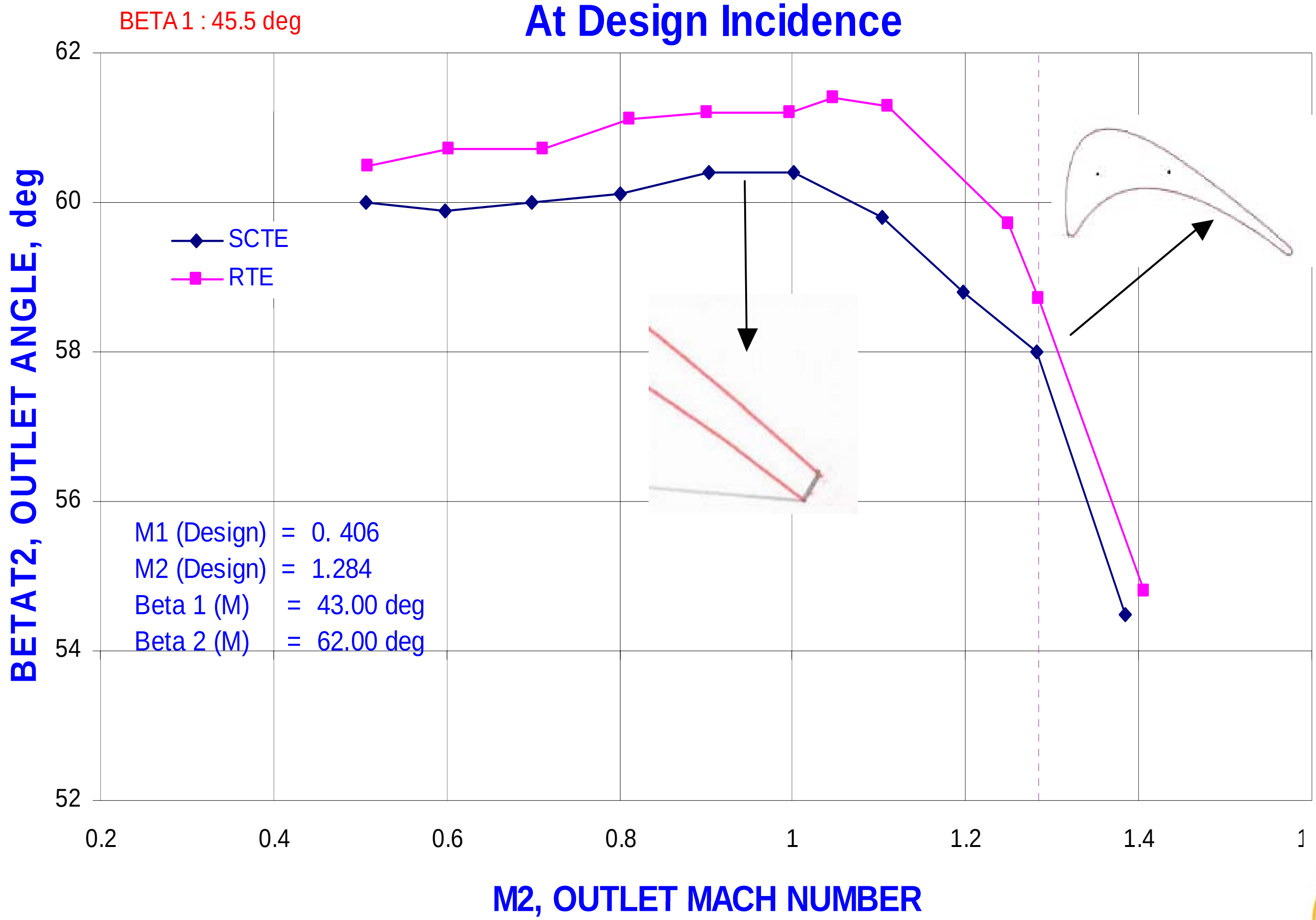


FIG. VARIATION OF OUTLET FLOW ANGLE WITH OUTLET MACH NUMI

EFFECT OF TRAILING EDGE GEOMETRY

COMPARISON OF RESULTS (RM2-PROFILE)

Round Trailing Edge & Cut Trailing edge

At Design Incidence

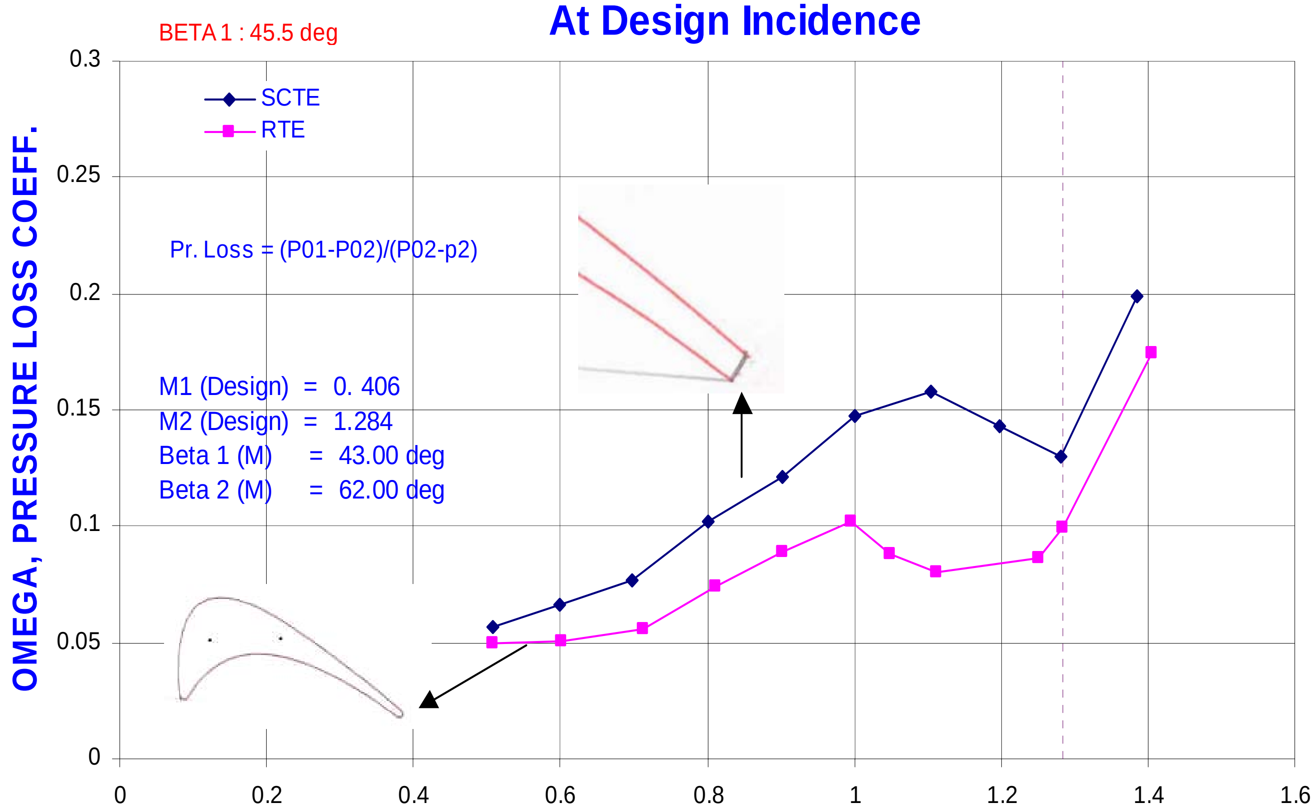


FIG. VARIATION OF PRESSURE LOSS COEFF. WITH OUTLET MACH NUMBER

EFFECT OF COOLANT FLOWS ON TURBINE CASCADE

- Unlike the conventional method of heating the main flow or using Carbon-di- oxide as the coolant to simulate the density ratios, an ingenious method of having the main flow at room temperature and cooling the coolant to a lower temperature has been adopted to simulate the density ratios.

- Coolant to mainstream temperature ratios of 0.5 and 0.9 were simulated.

- The actual aspect ratio of trailing edge slots of the NGV was maintained using two partition plates in the cascade assembly.

Configurations:

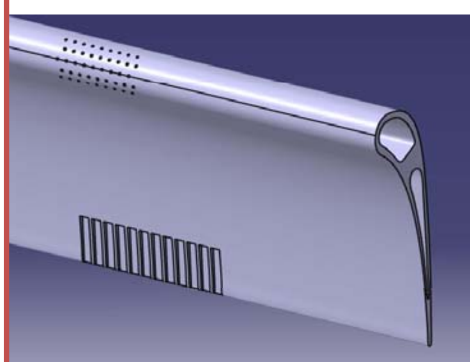
I - Base profile, without coolant flow
II - LE & TE coolant flows at $T_c/T_g = 0.9$, $P_c/P_g = 1.02$
III - LE & TE coolant flows at $T_c/T_g = 0.5$, $P_c/P_g = 1.04$
IV - TE coolant flow at $T_c/T_g = 0.9$, $P_c/P_g = 1.02$
V - TE coolant flow at $T_c/T_g = 0.5$, $P_c/P_g = 1.04$

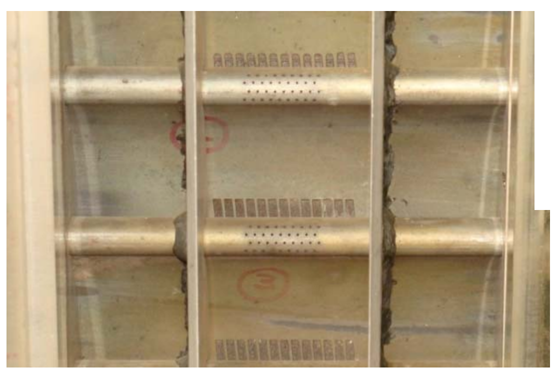
Simulation of actual coolant to gas density ratios in cascade tests

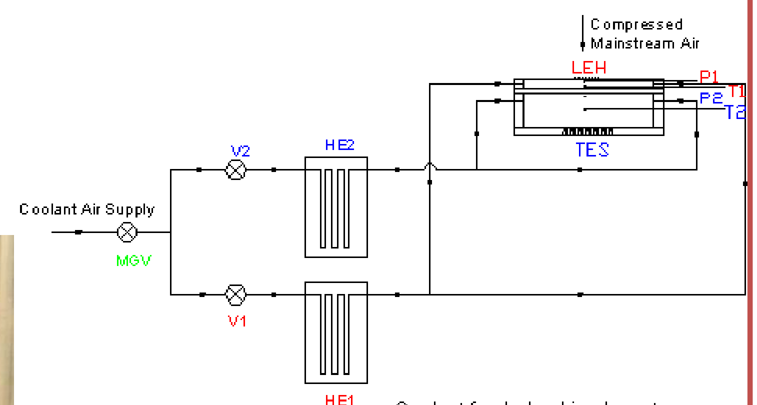
Motivation: To study the effect of coolant flows on the loss characteristics of gas turbine profiles

An ingenious method of having the main flow at room temperature and cooling the coolant to a lower temperature was used to simulate the temperature ratios. The coolant air was passed through a heat exchanger immersed in a bath of liquid nitrogen to attain low temperatures.

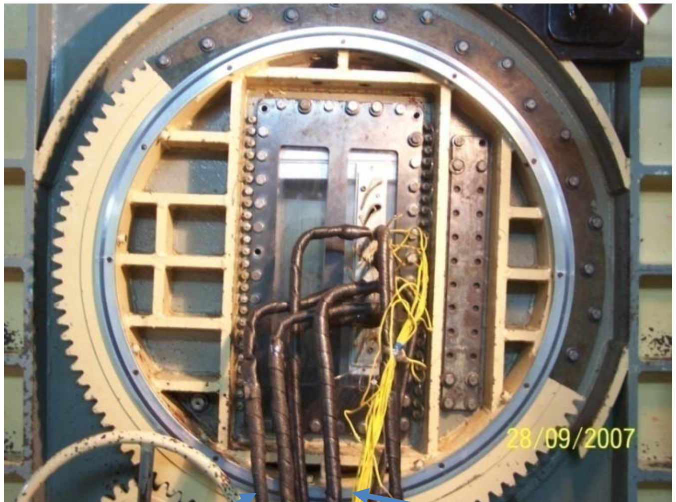
The actual aspect ratio of trailing edge slots of the NGV was maintained using two partition plates in the cascade assembly.







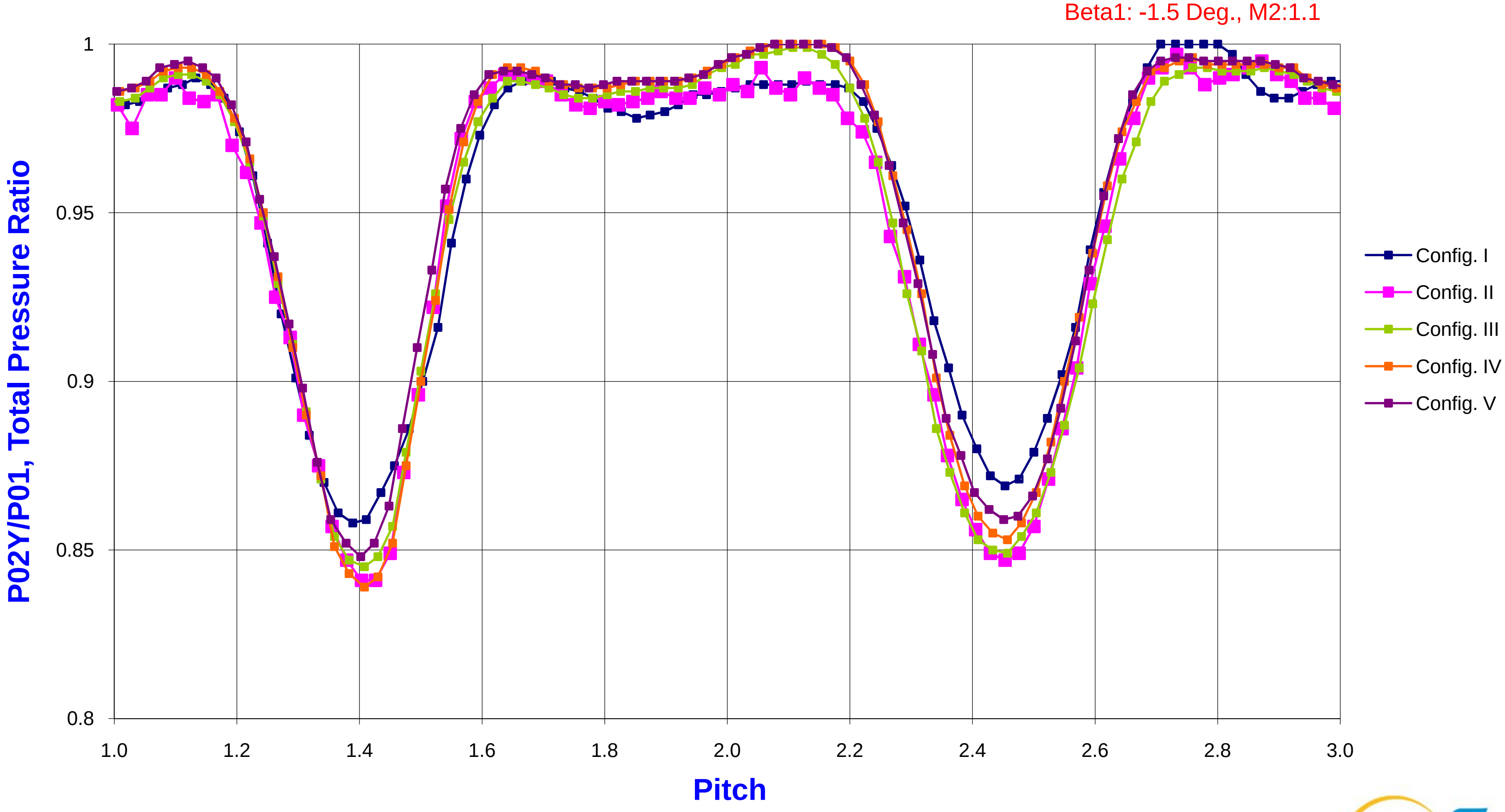
Coolant feed plumbing layout



Insulated coolant feed lines   Thermocouple connections   Heat exchanger

Coolant flow control valves

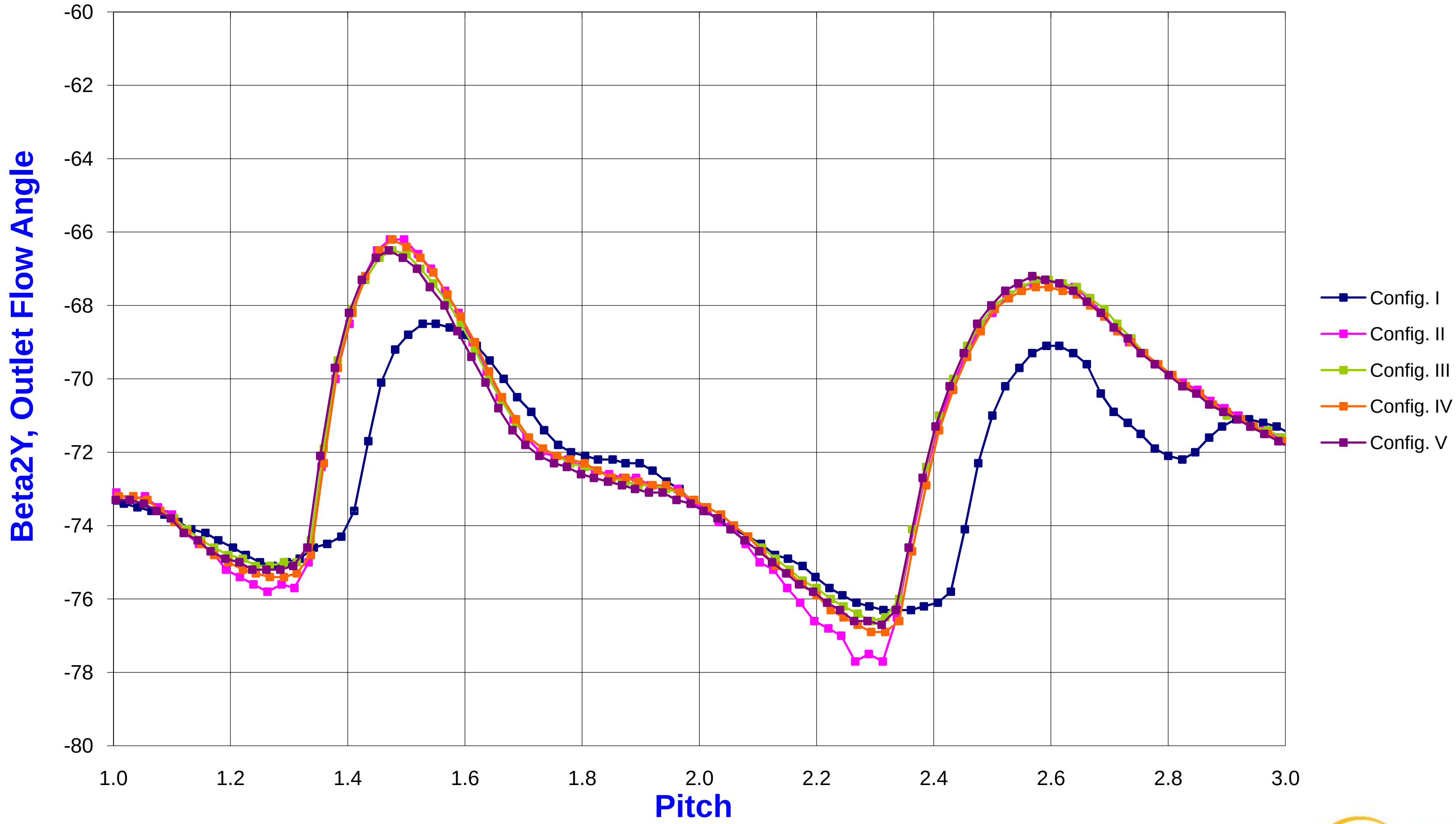
EFFECT OF COOLANT FLOWS ON TOTAL PRESSURE RATIO OF A TURBINE NOZZLE CASCADE



P02/P01 V/S PROBE TRAVERSE

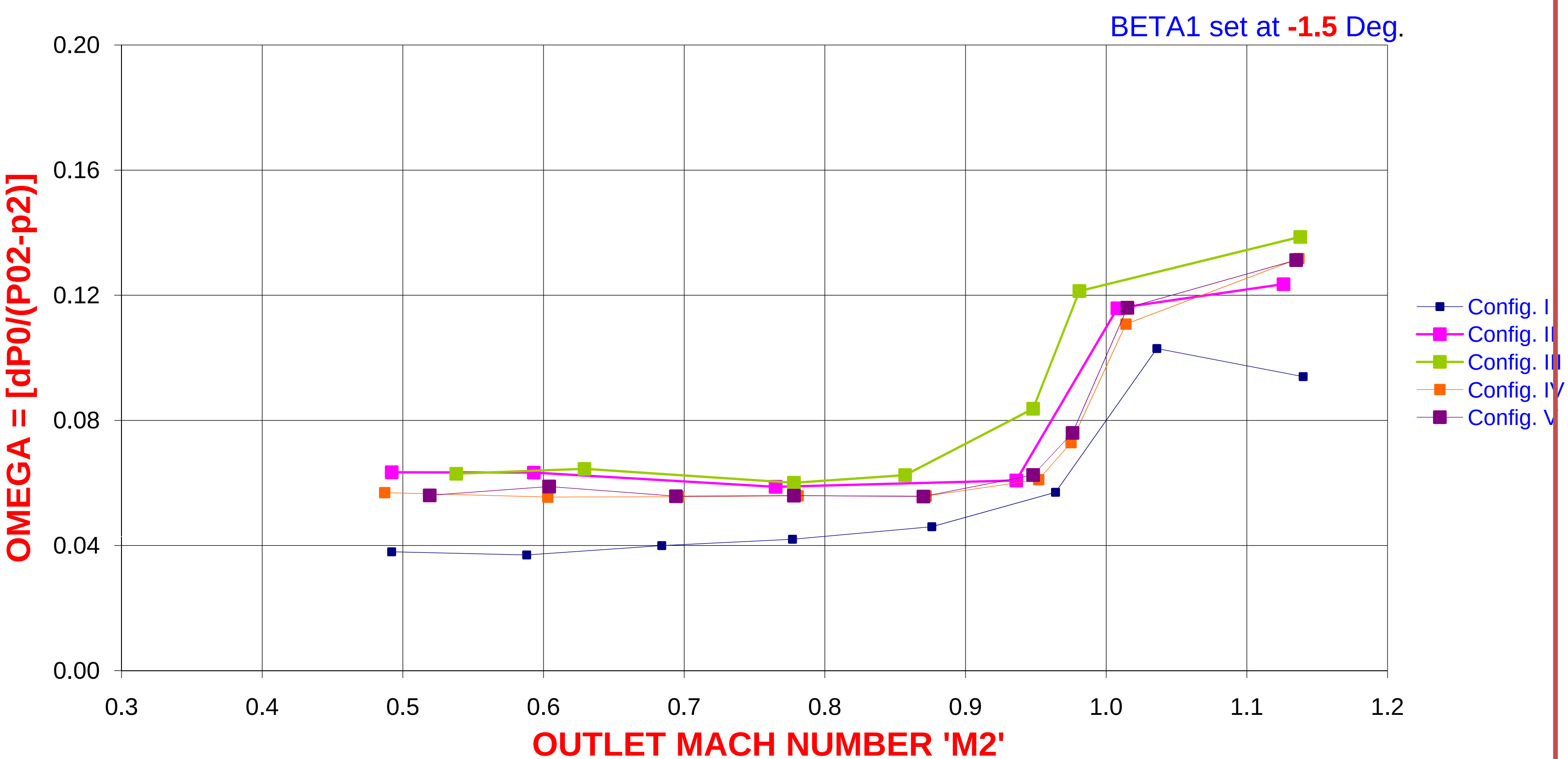
EFFECT OF COOLANT FLOWS ON OUTLET FLOW ANGLE OF A TURBINE NOZZLE CASCADE

Beta1: -1.5 Deg, M2:1.1



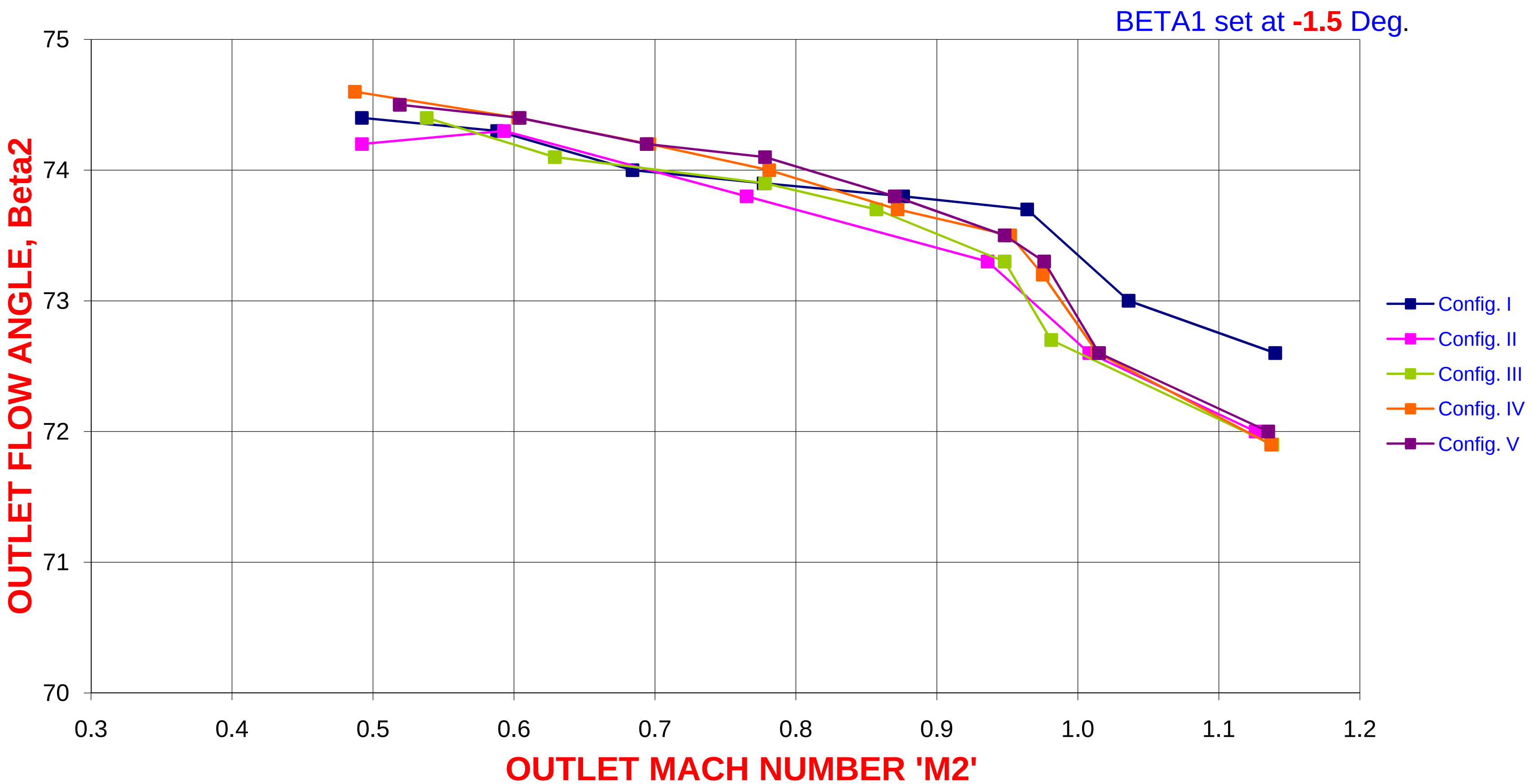
OUTLET FLOW ANGLE V/S PROBE TRAVERSE

EFFECT OF COOLANT FLOWS – INTEGRATED LOSS COEFFICIENT



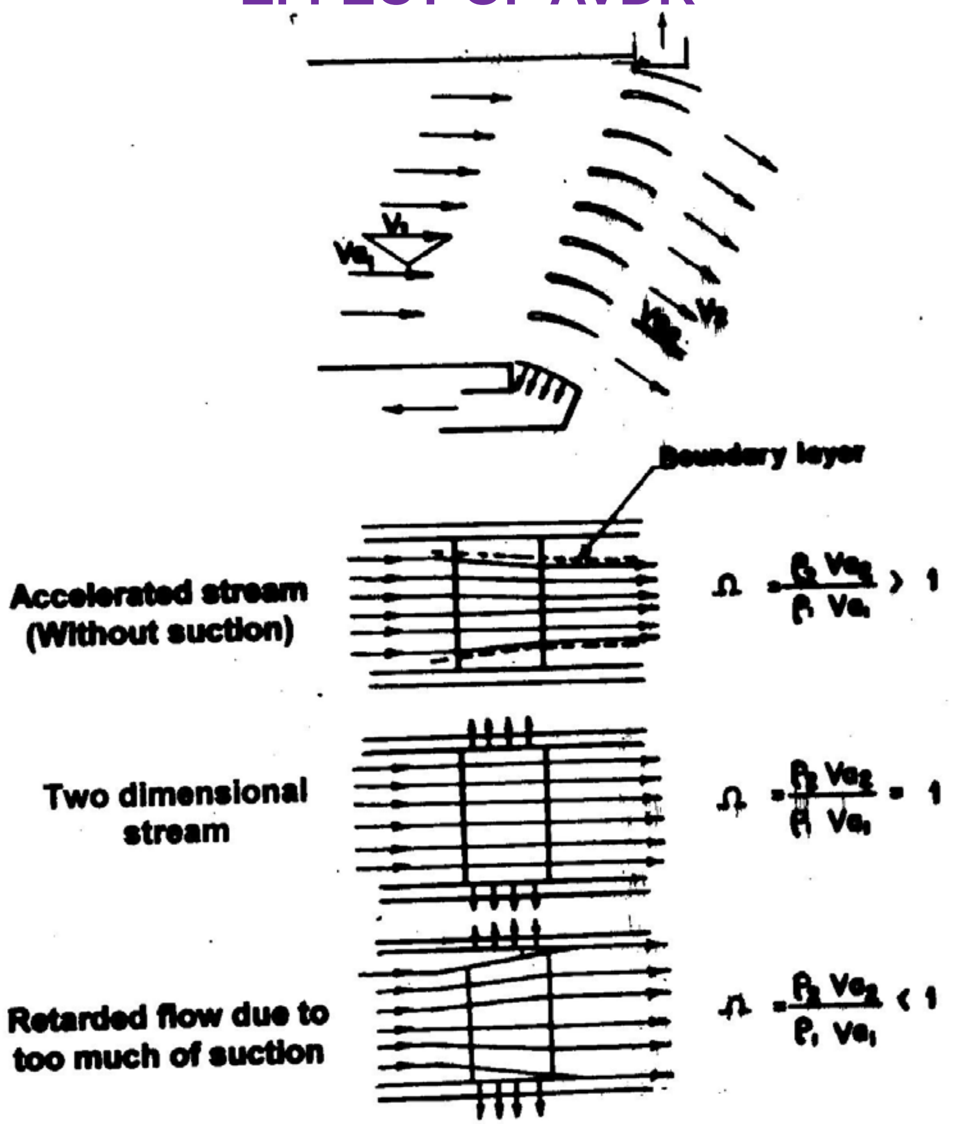
VARIATION OF PRESSURE LOSS COEFFICIENT WITH OUTLET MACH NUMBER

EFFECT OF COOLANT FLOWS – INTEGRATED OUTLET FLOW ANGLE



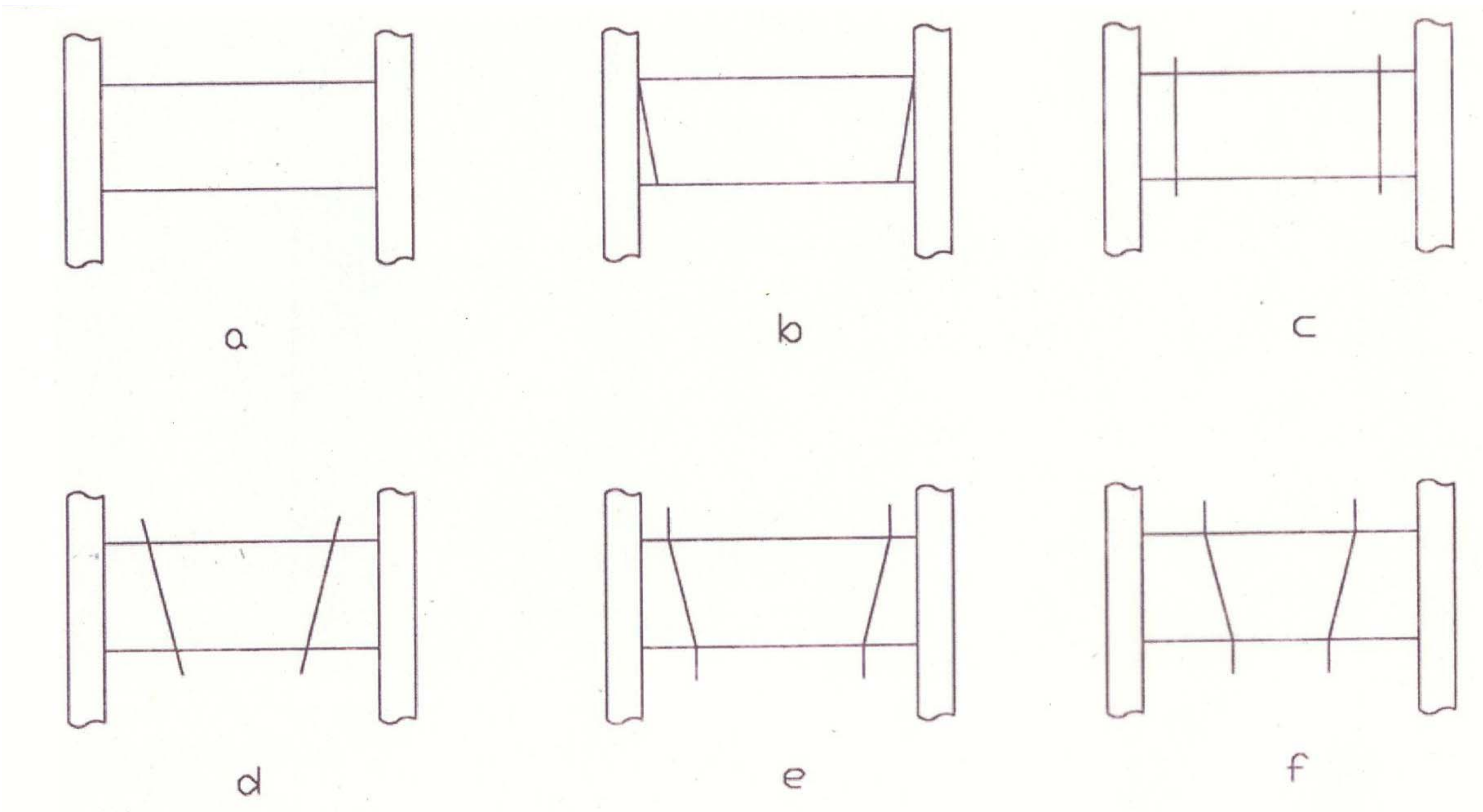
VARIATION OF OUTLET FLOW ANGLE WITH OUTLET MACH NUMBE

EFFECT OF AVDR

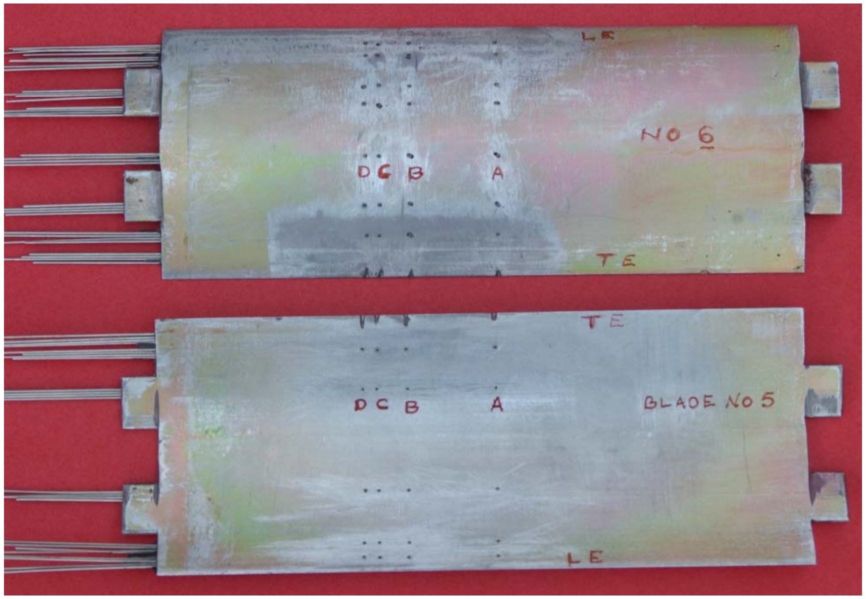


DEFINITION OF AXIAL-VELOCITY-DENSITY RATIO

EFFECT OF AVDR



USE OF PARTITION PLATES


LE
NO 6
D C B A
TE
TE
D C B A
BLADE NO 5
LE

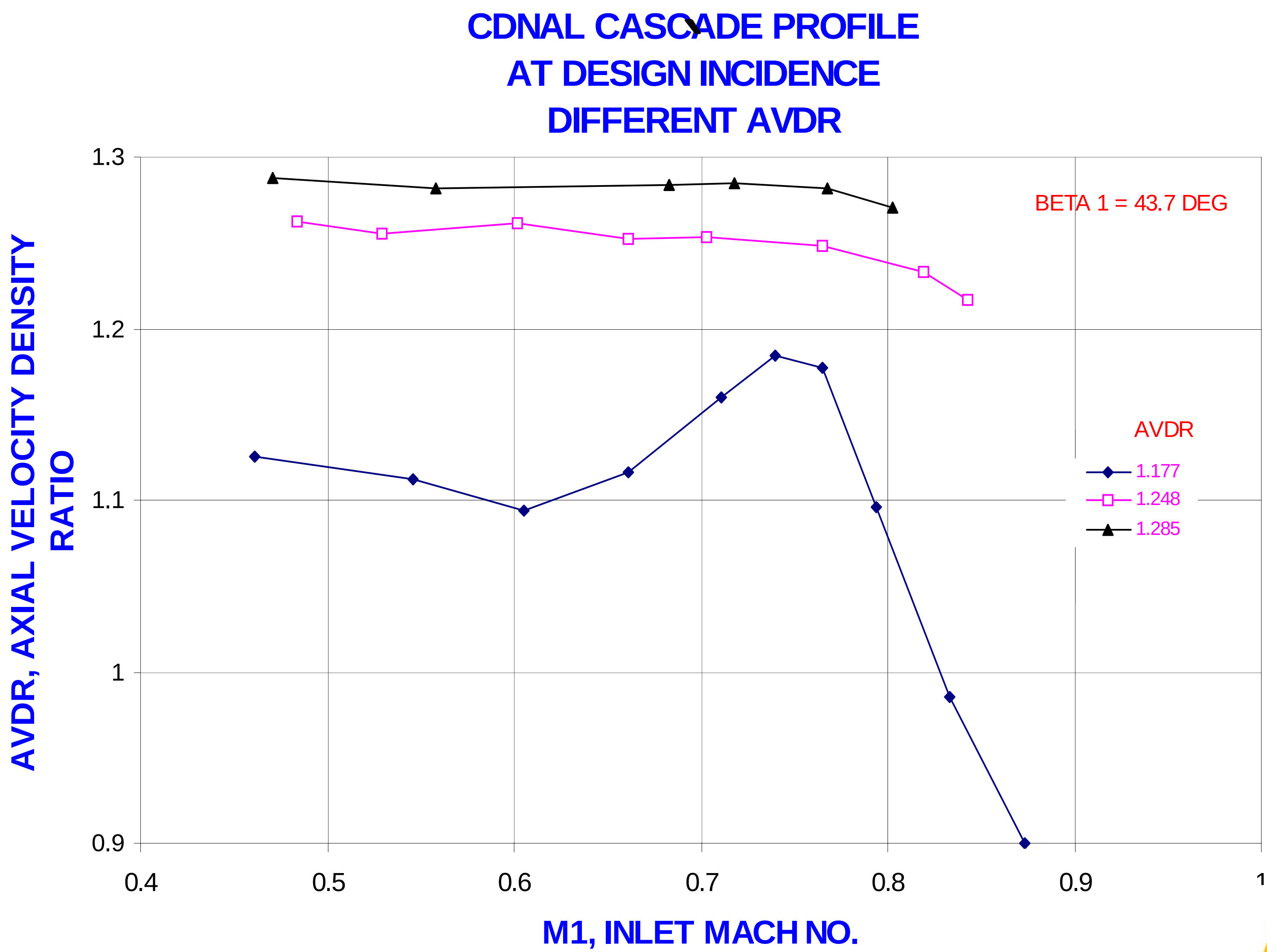


FIG. 60 VARIATION OF AXIAL VELOCITY DENSITY RATIO WITH INLET MA(

CDNAL CASCADE PROFILE
AT DESIGN INCIDENCE
EFFECT OF AVDR

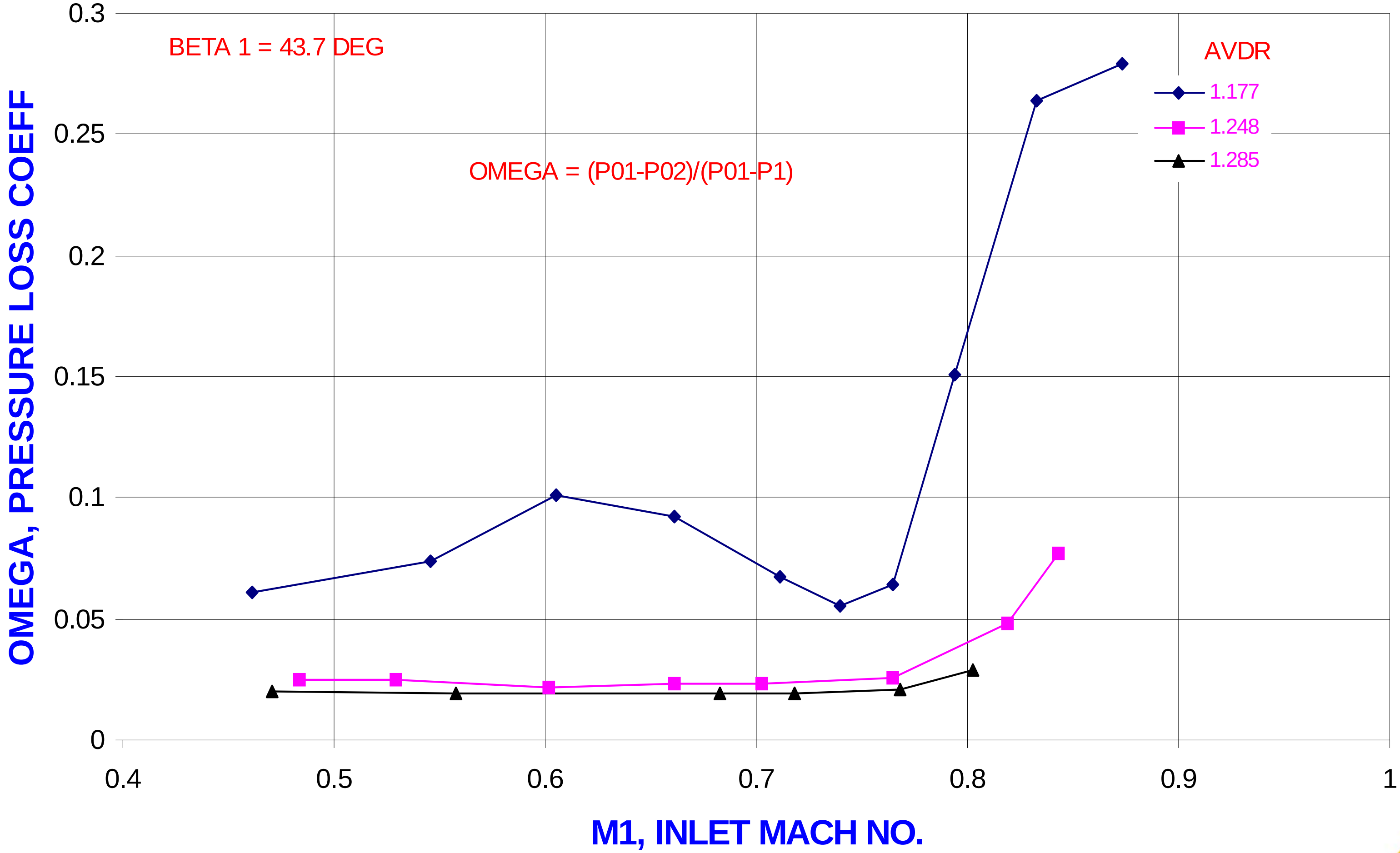
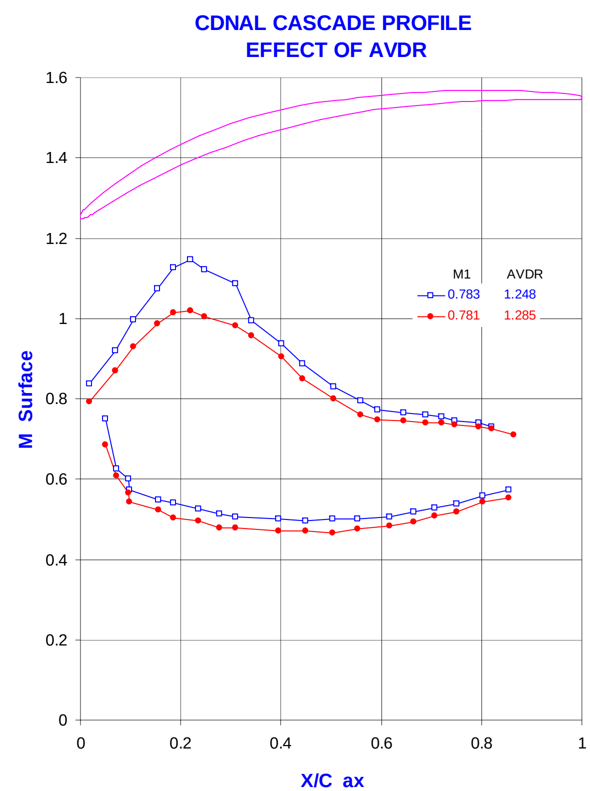


FIG. 61 VARIATION OF PRESSURE LOSS COEFF. WITH INLET MACH N


CDNAL CASCADE PROFILE
EFFECT OF AVDR
M Surface
X/C ax
M1
AVDR
0.783
1.248
0.781
1.285
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6